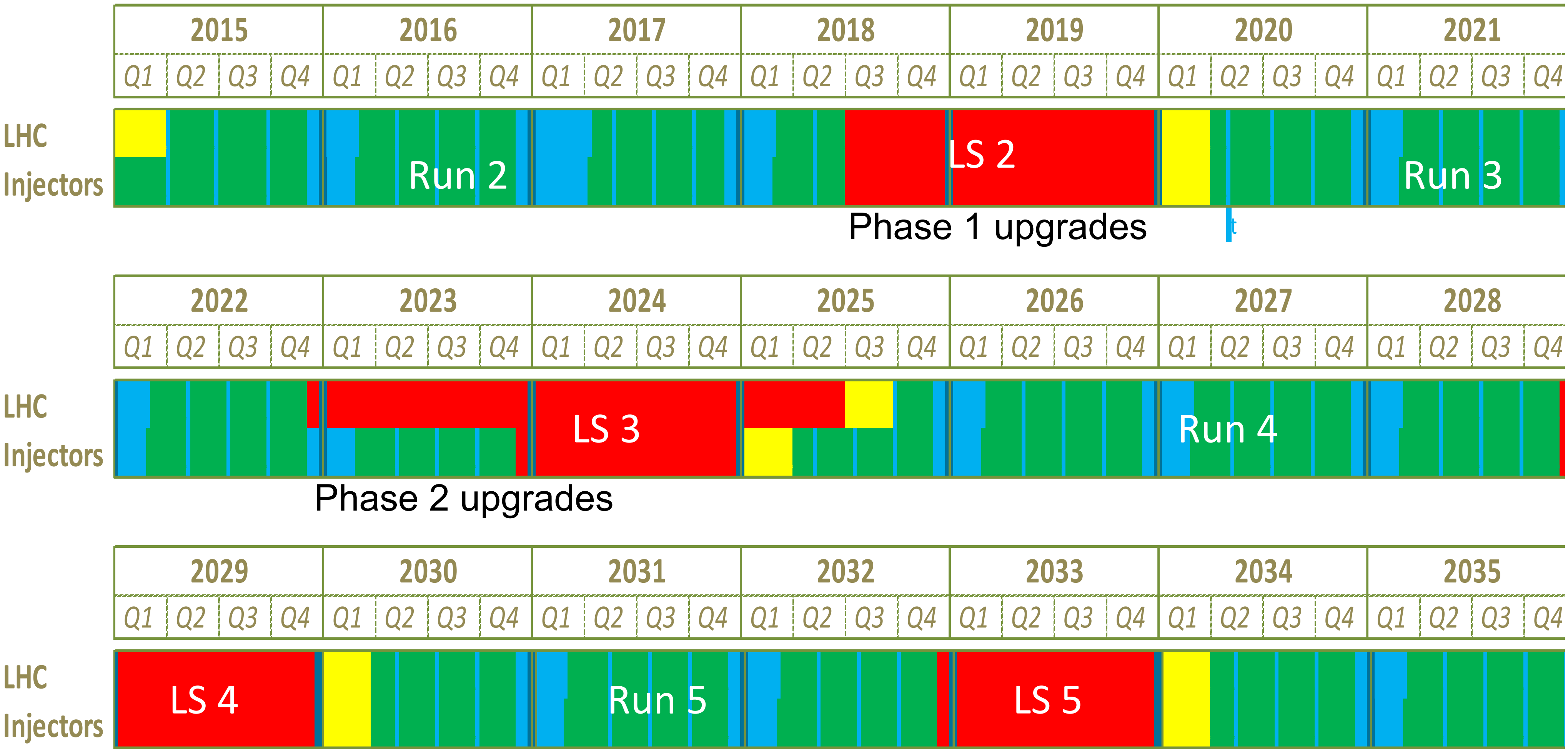
Physics of HL-LHC

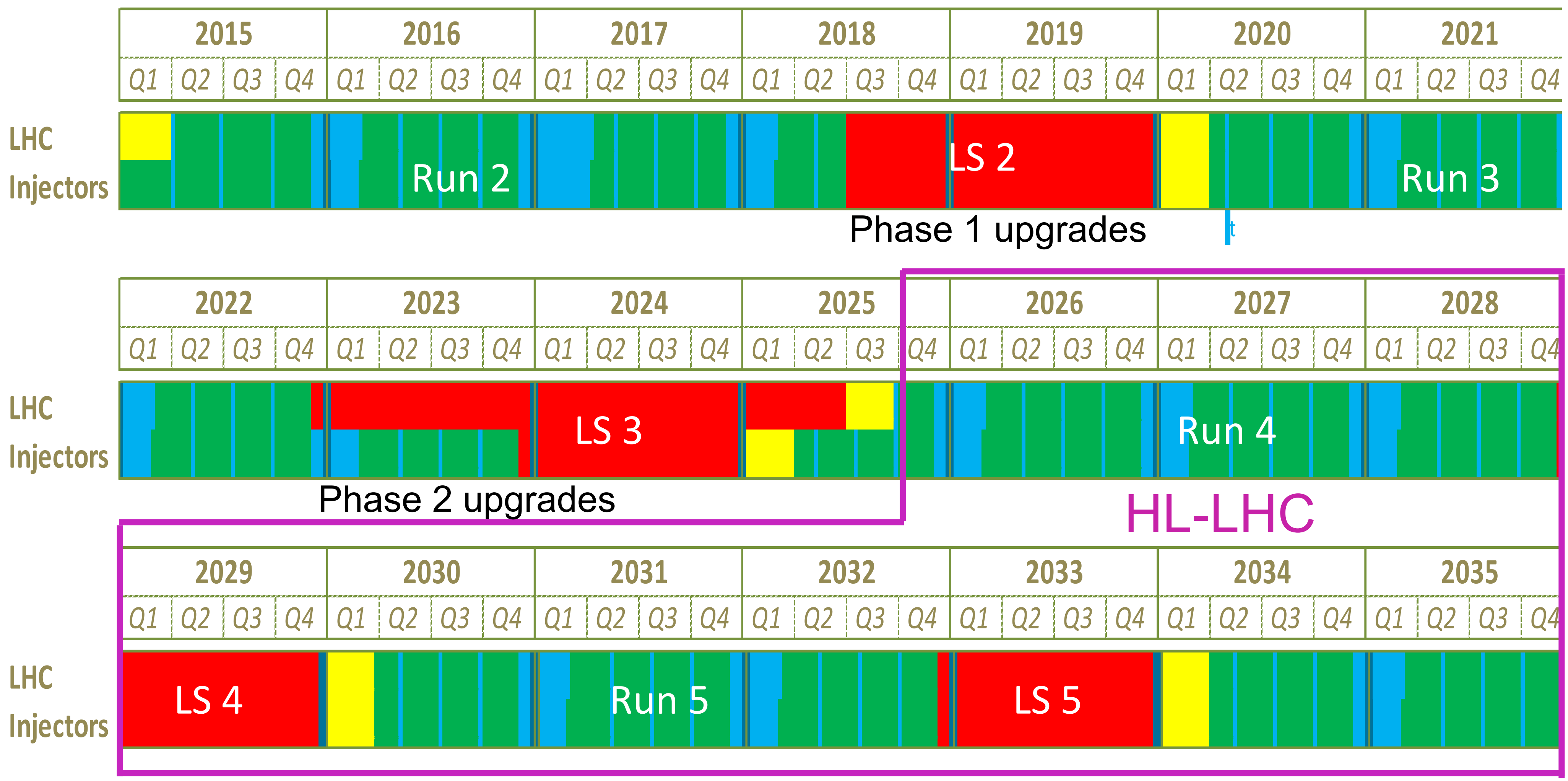
Reinhard Schwienhorst
Enigmass Visitor
Michigan State University/LPSC Grenoble

Introduction

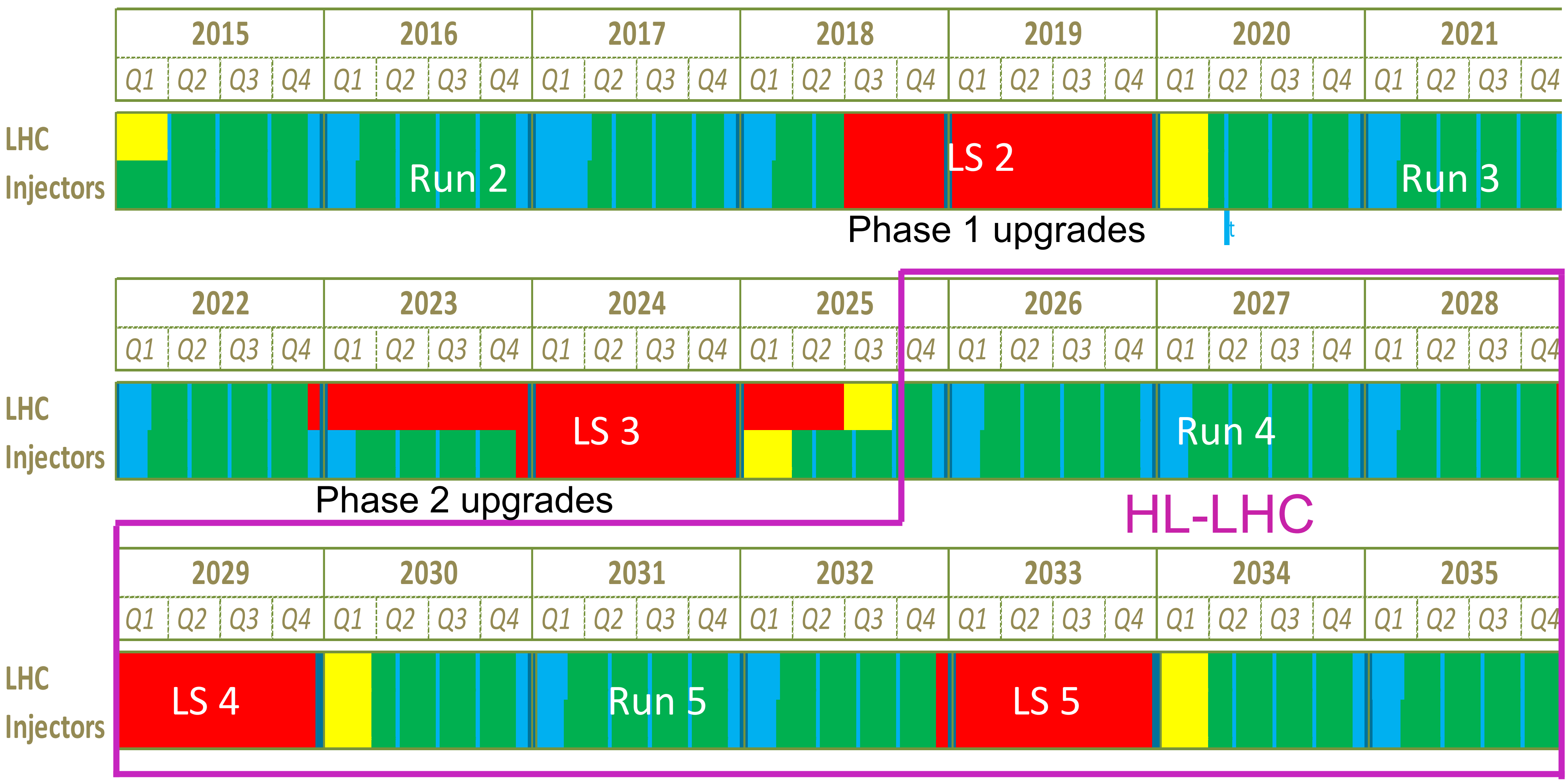
LHC schedule



LHC schedule



LHC schedule



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2021

Q4

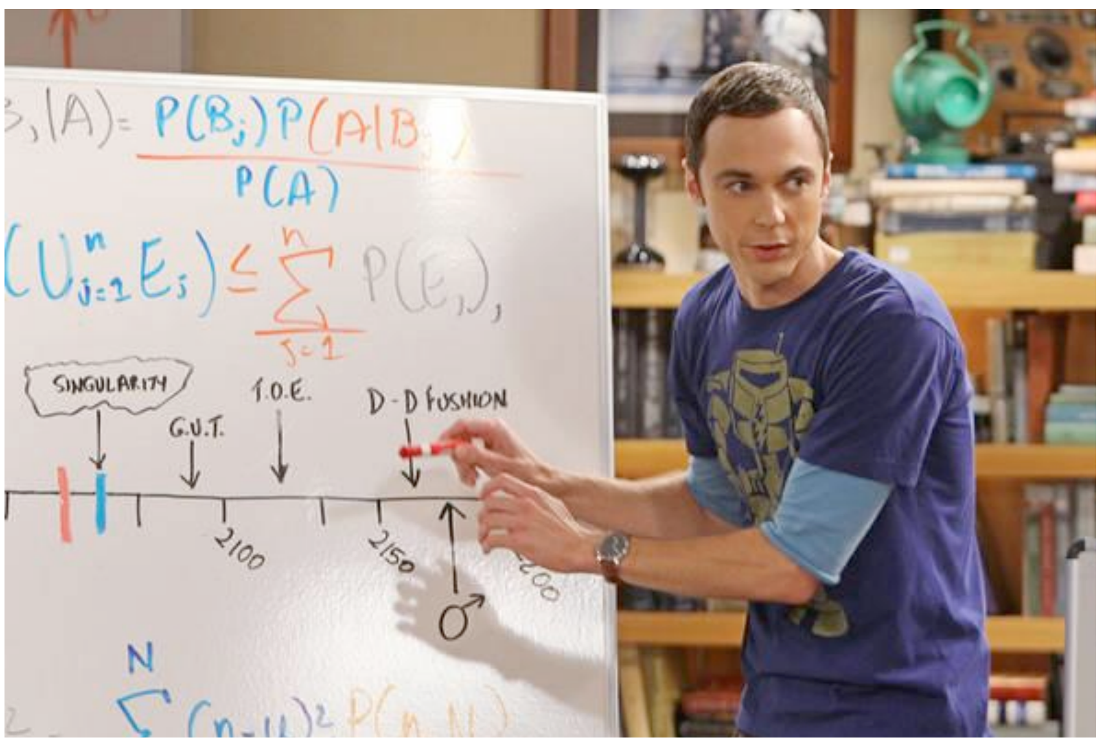
LH

2025

Let's travel to 2025

Let's travel to 2025

The world in 2025



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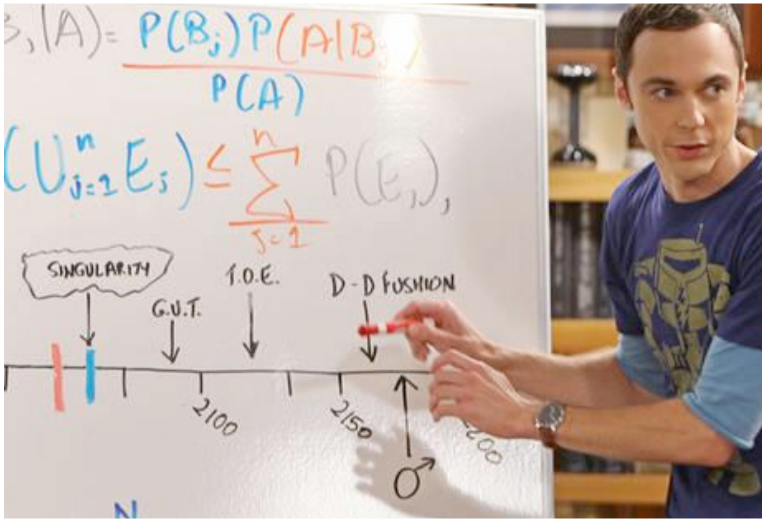
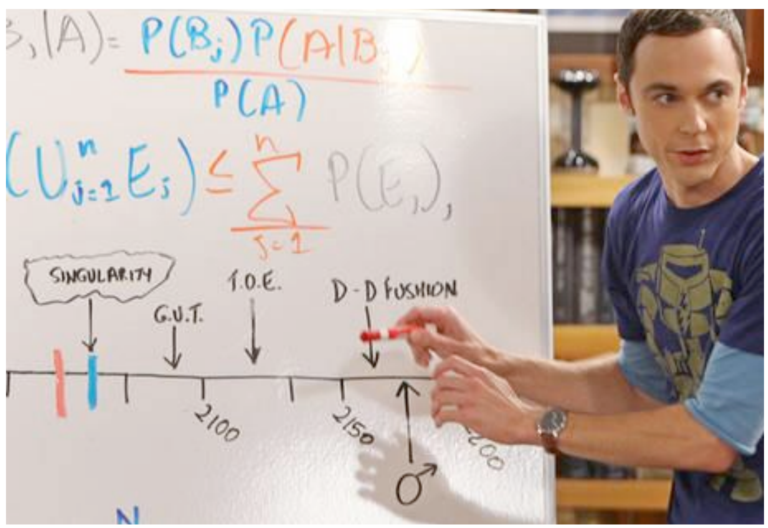
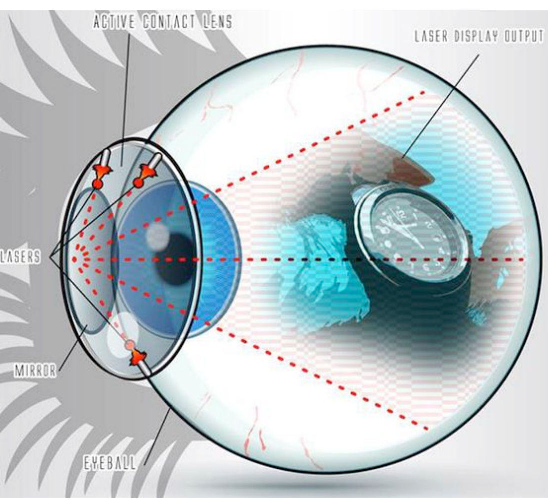
The world in 2025

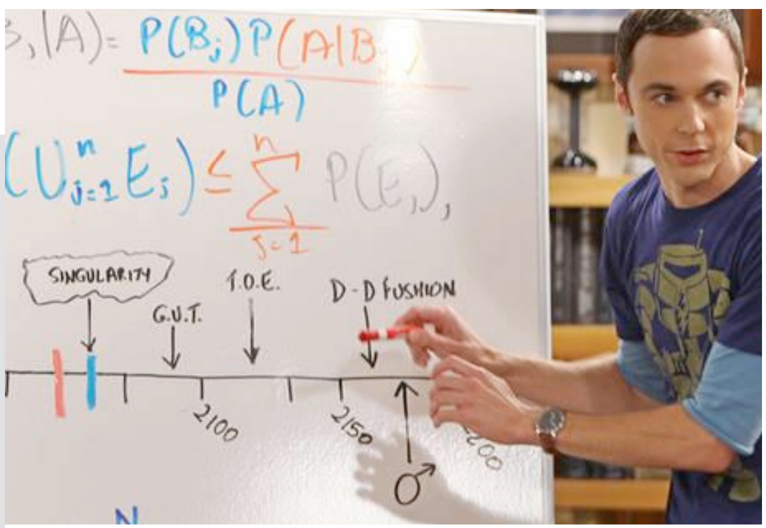


The world in 2025

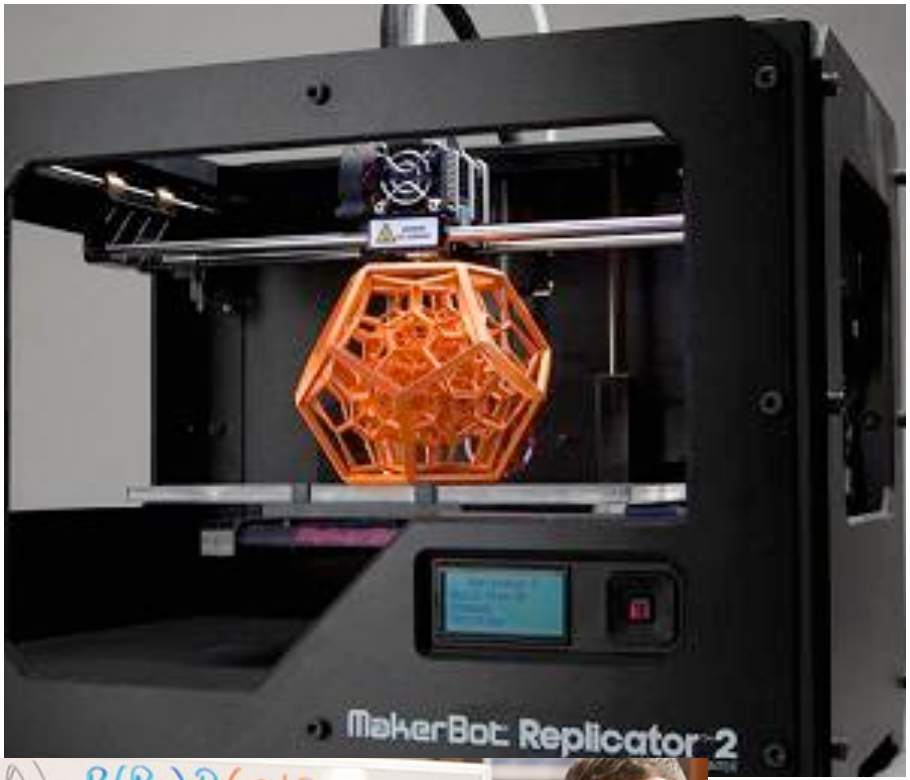


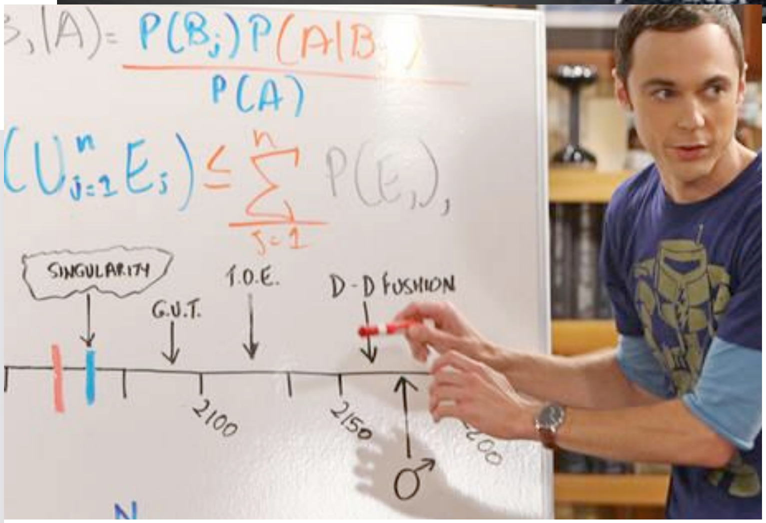
The world in 2025

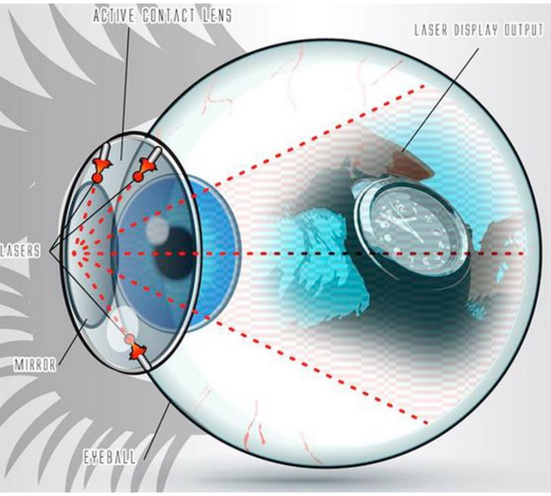




The world in 2025







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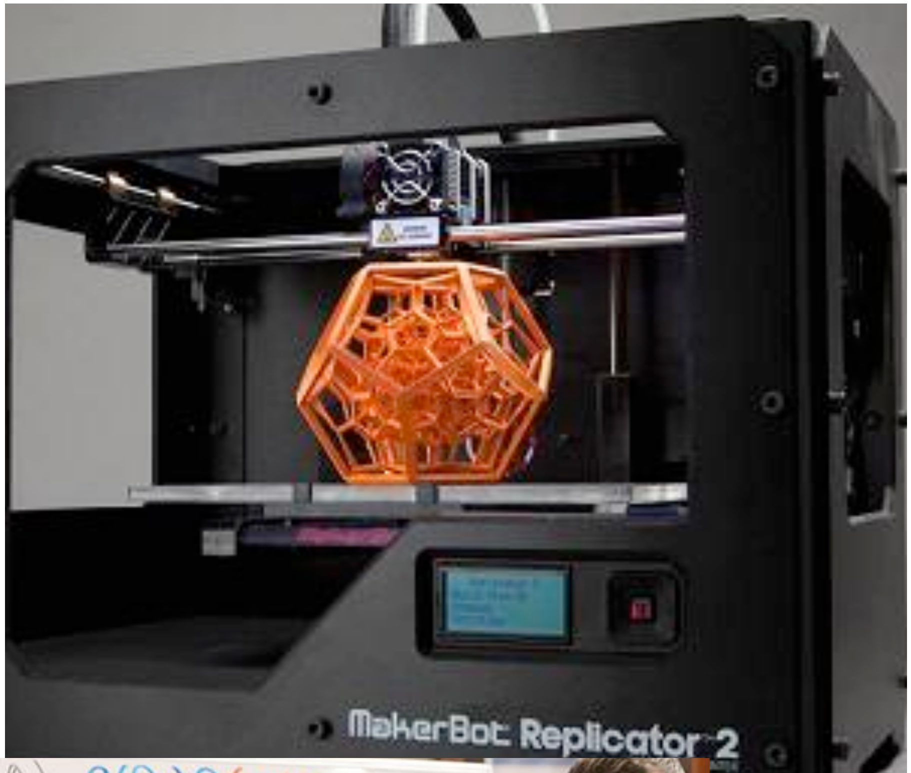

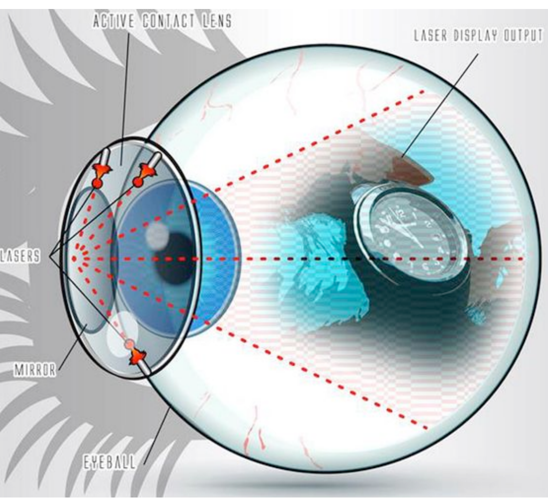

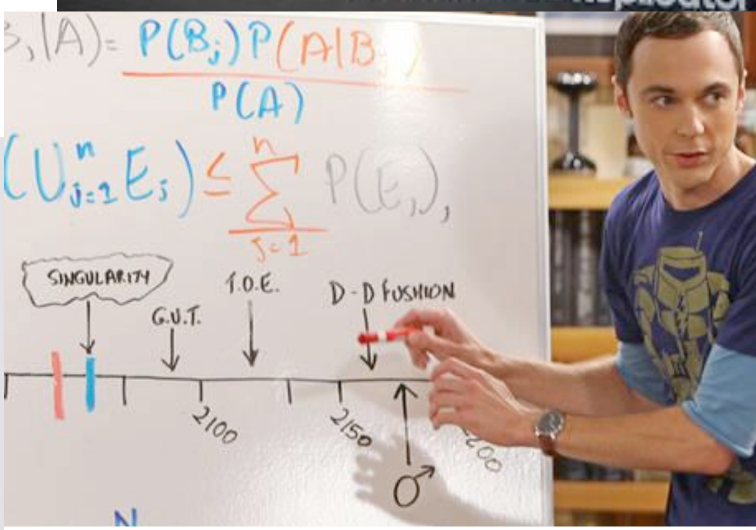

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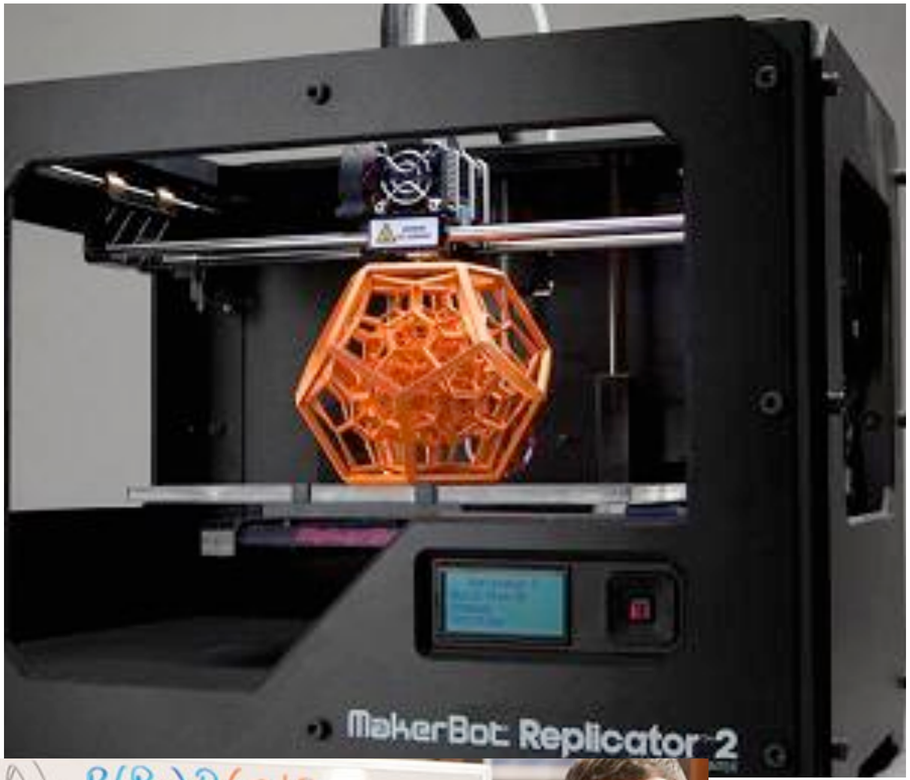

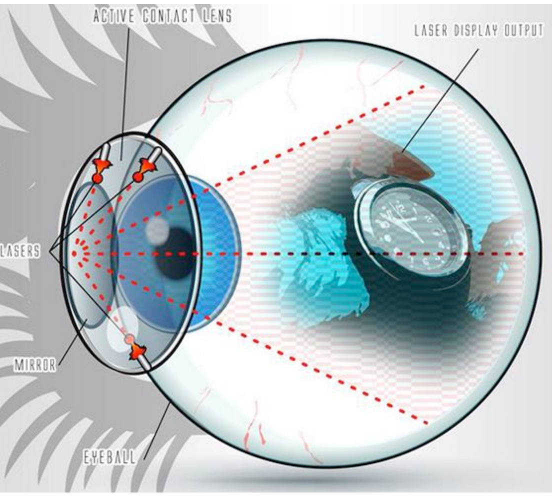

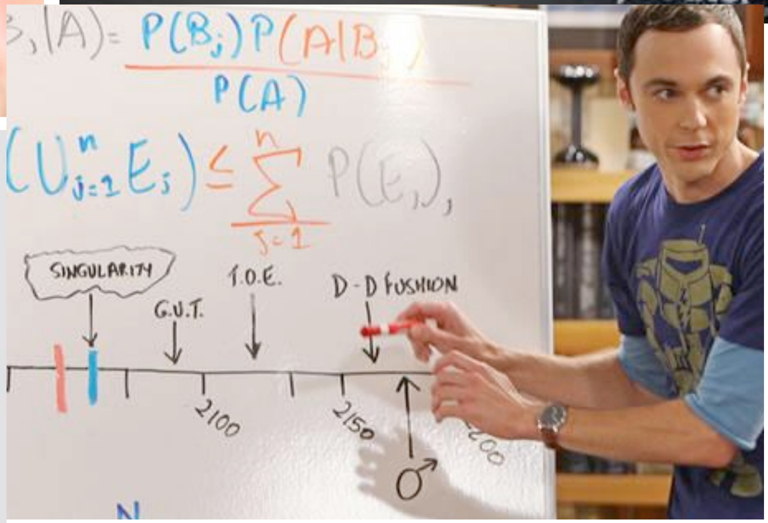

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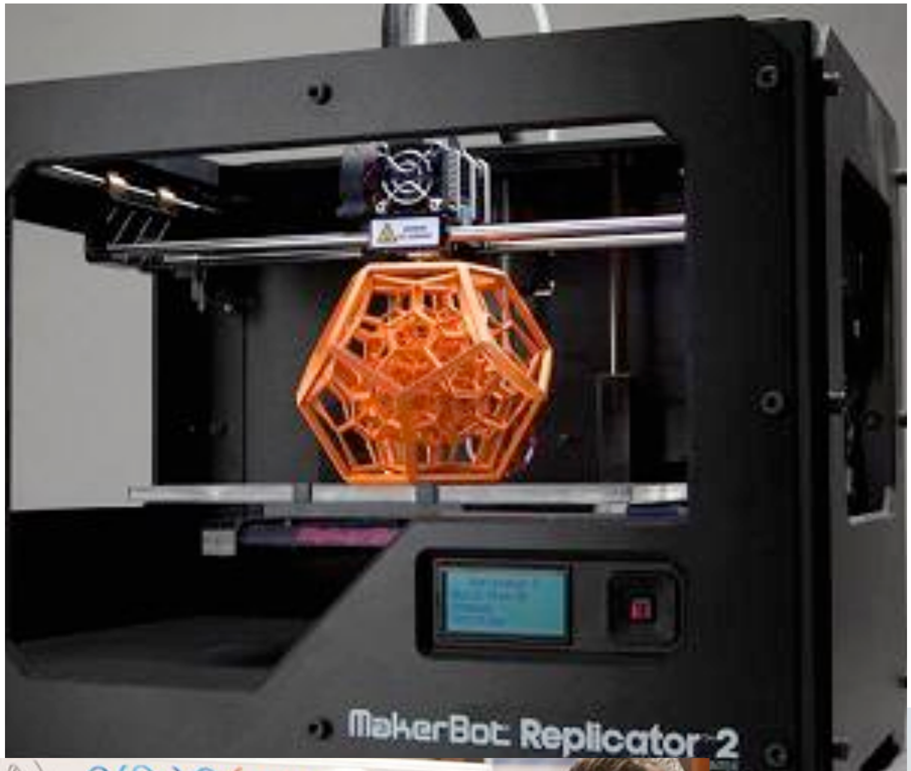

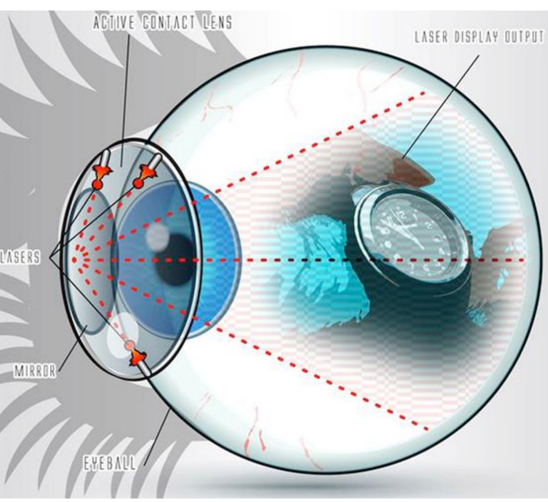

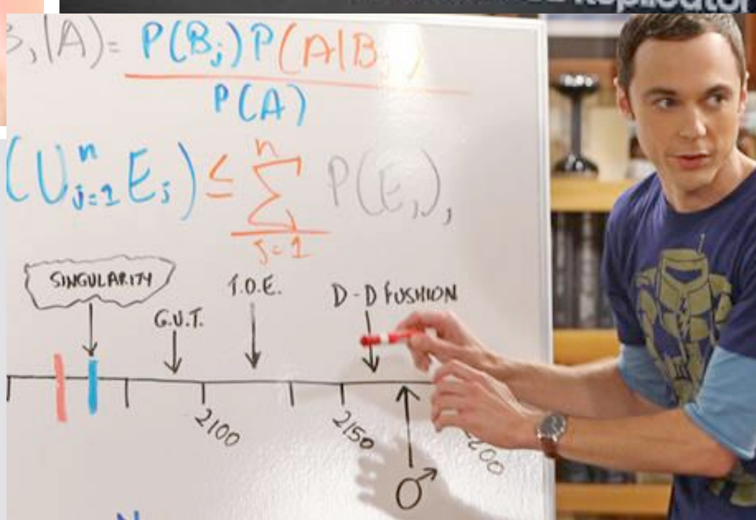

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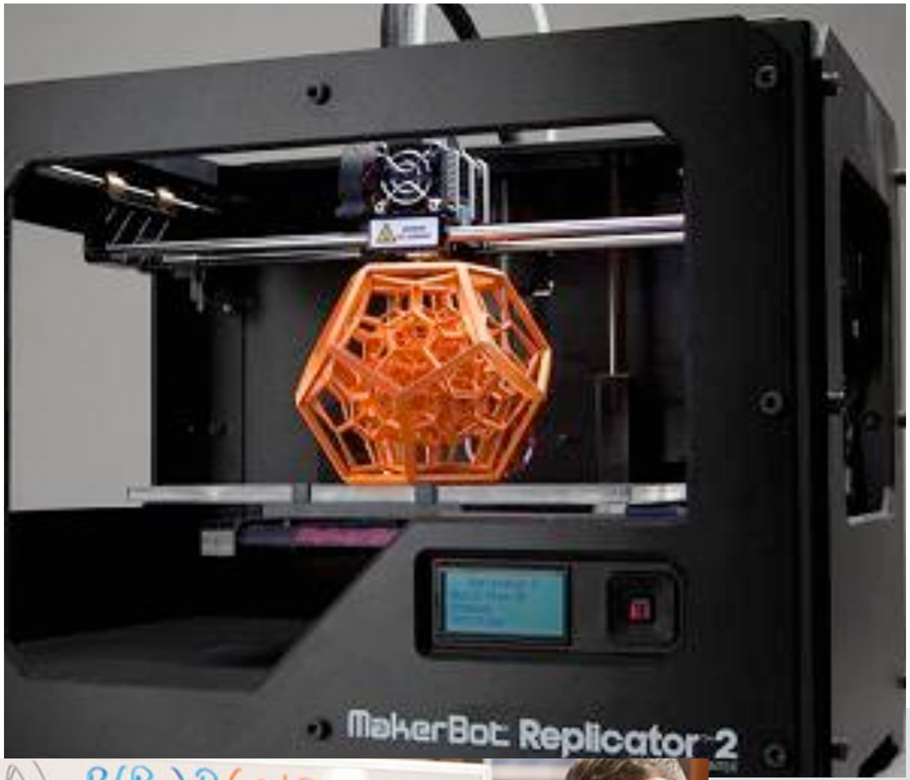
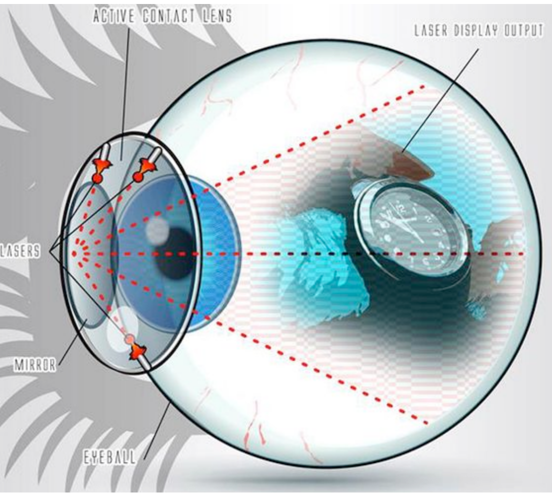
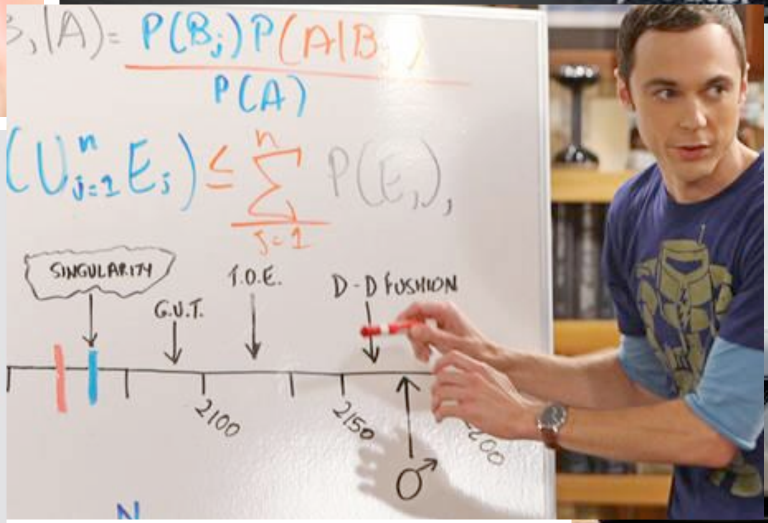




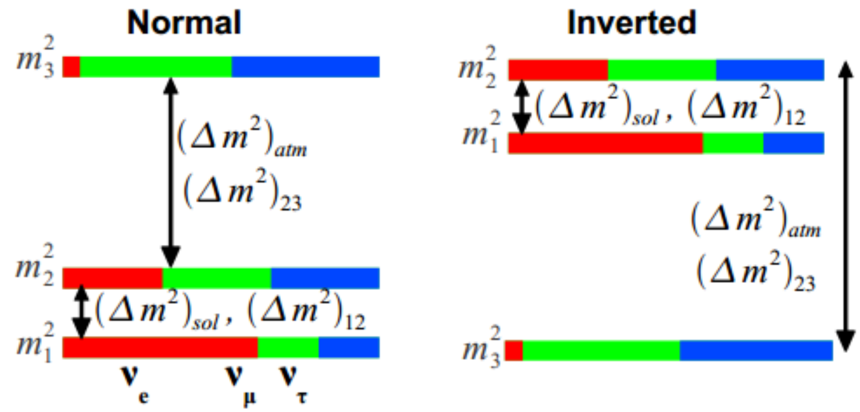


Particle physics in 2025

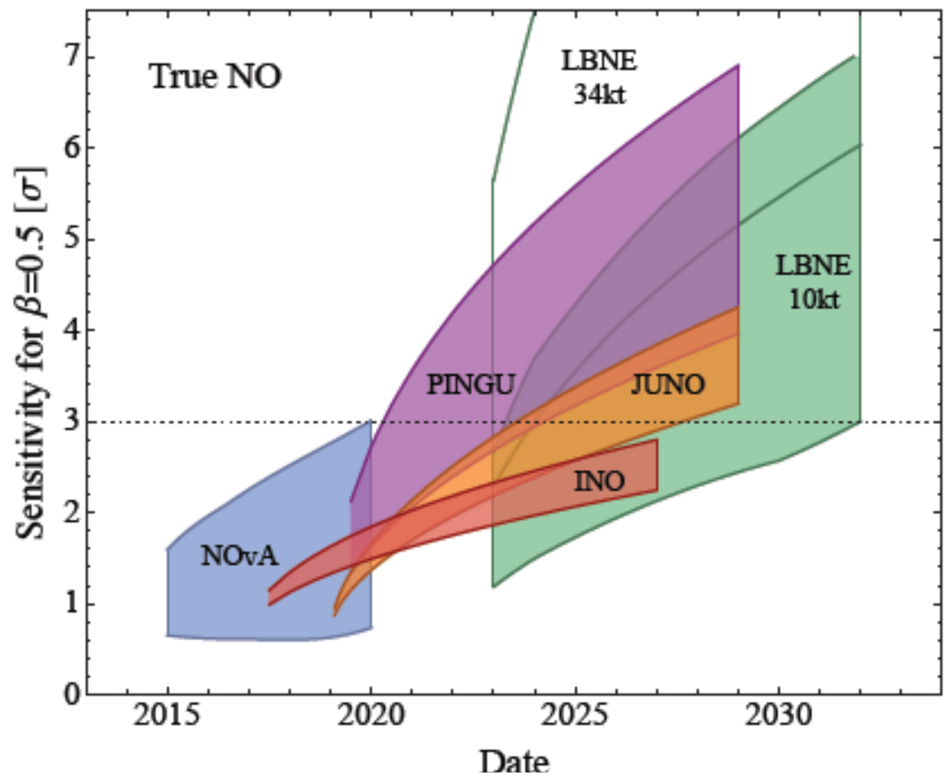
- Cosmology with LSST
  - Dark matter, dark energy
- Lepton flavor violation
  - g-2
  - Mu2e
  - Probe energy scales of ~10^4 TeV
- Neutrinoless double-beta decay?
  - Probe energy scales of ~10^{15} TeV
- Proton decay?
  - Probe energy scales of ~10^{15} TeV
- ILC construction?
- 100 TeV collider planning?
  - Future Circular Collider

Particle physics in 2025

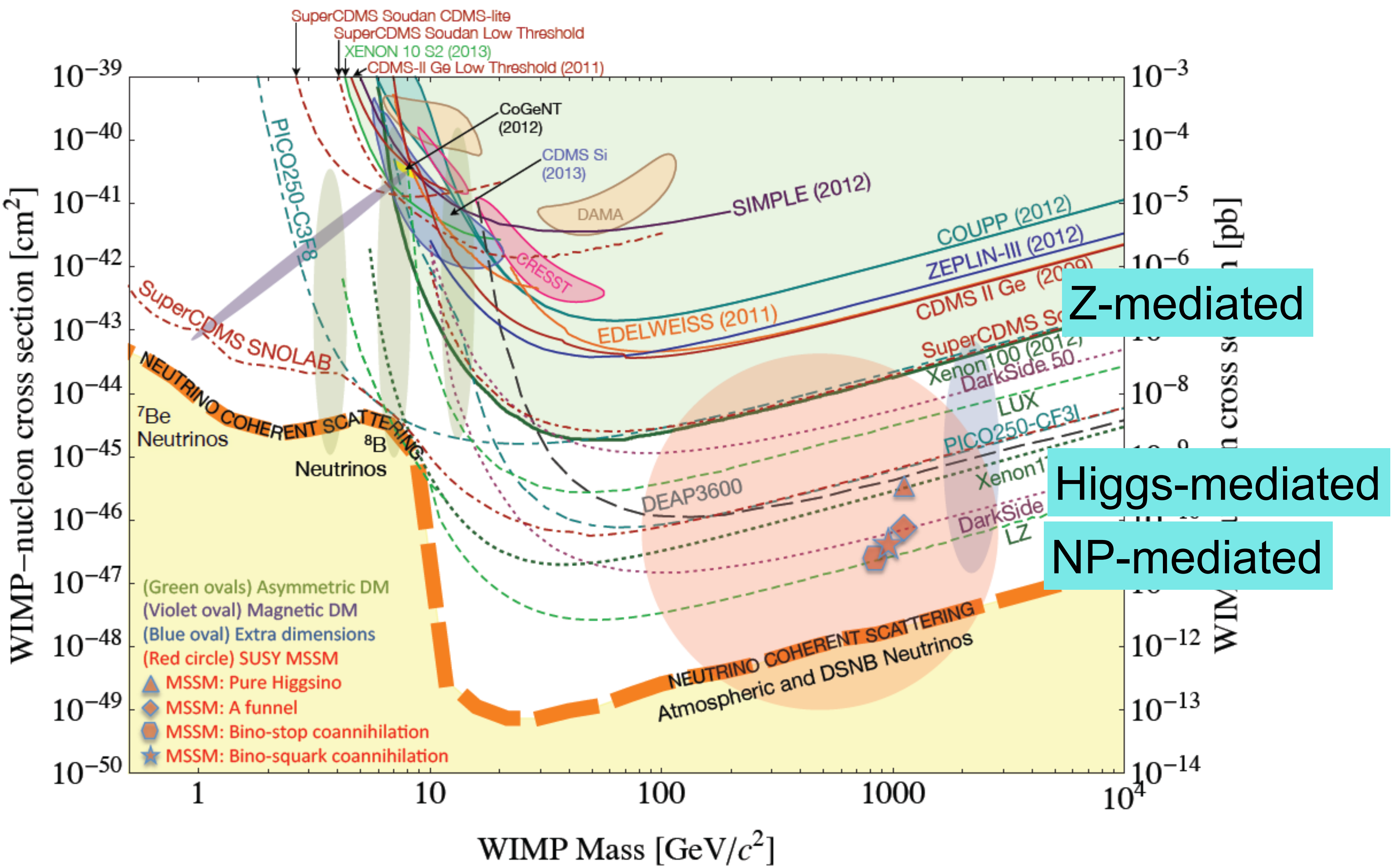
- Neutrinos: First results on mass hierarchy



- Many neutrino measurements
  - Accelerator
  - Atmospheric
  - Solar
  - Astronomical
  - Supernova

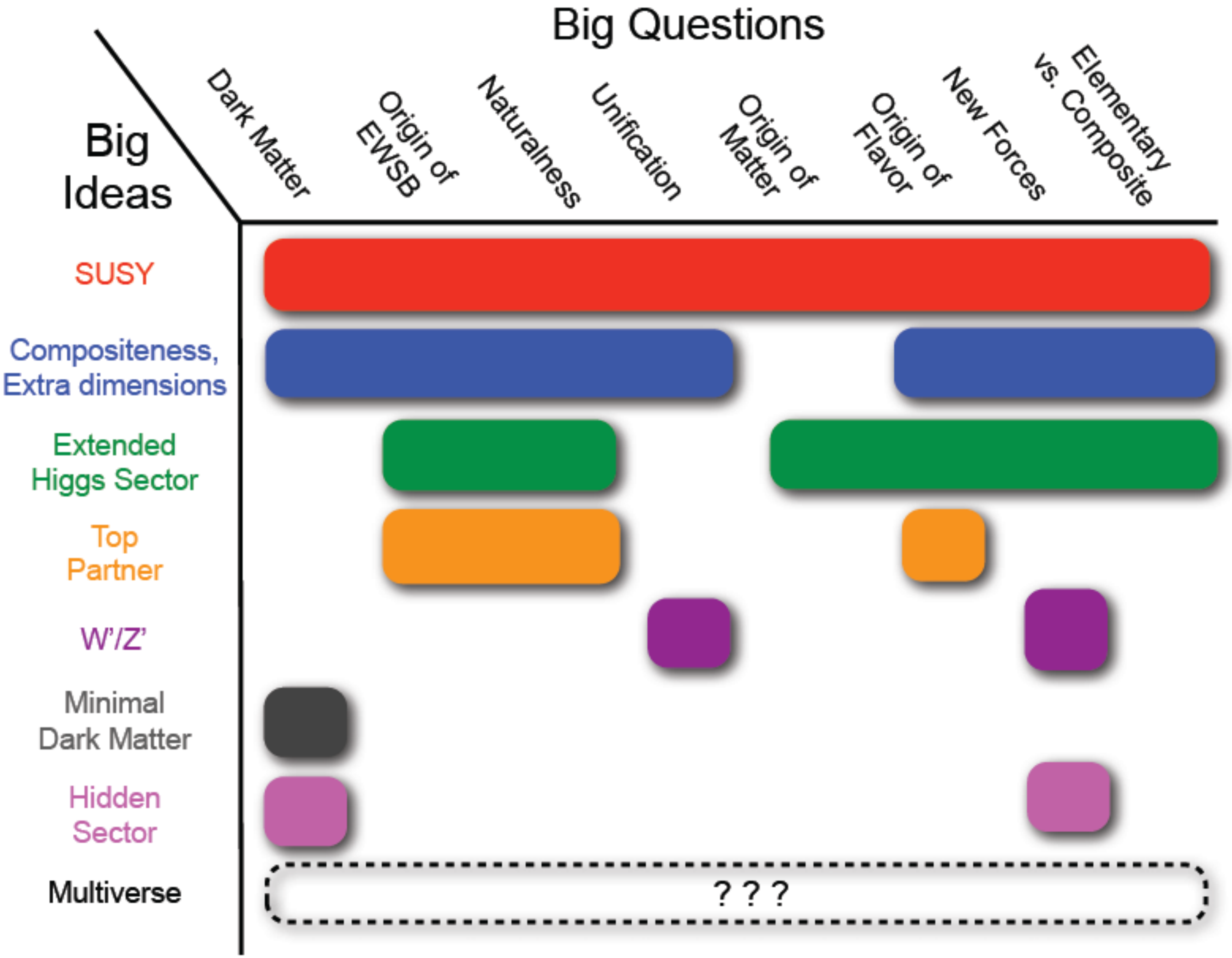


Physics in 2025: Direct dark matter detection



- Also indirect detection of DM annihilation in sun or galaxies

HL-LHC physics questions



Snowmass 2013

HL-LHC physics question

- Higgs - high-precision measurements
  - Find/characterize the full Higgs sector
  - Look for deviations from SM predictions in Higgs couplings
- W, Z, top - high-precision measurements
  - Implications for Higgs
  - Look for deviations from SM predictions
- Flavor physics
  - How are quark and lepton sectors related?
  - What are the symmetries and how are they broken?
  - Rare decays
- Dark matter - characterize it
  - Find it at LHC
  - Study its properties and couplings
- New particles/new physics
  - Study particles discovered in Run II
  - Follow up on hints from Run II

HL-LHC physics question

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Collider theory calculations in 2025

Process	Calculation
tt + j(j)	dσ(NWA top decays) @ NNLO QCD + NLO EW
tt + V	dσ(top decays) @ NLO QCD + NLO EW
single-top	dσ(NWA top decays) @ NNLO QCD + NLO EW
3j	dσ @ NNLO QCD + NLO EW
γ +j	dσ @ NNLO QCD + NLO EW
HH	dσ @ NLO QCD with m_t/m_b dependence
H	dσ @ NNNLO QCD
VV’	dσ @ NLO QCD + NLO EW

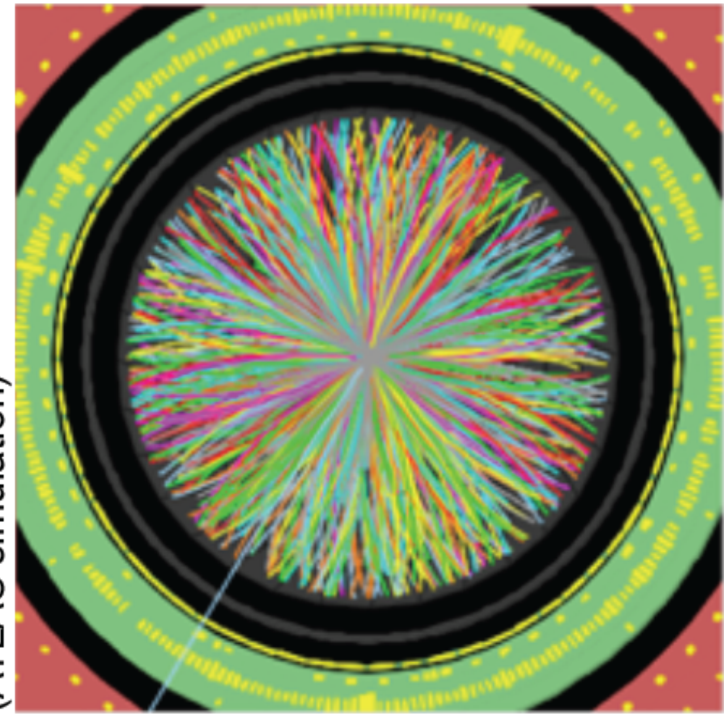
- Expect to have predictions at ~1% level or better
- Expect to have automatic tools for NNLO QCD and NLO EW calculations
  - Including decays and off-shell particles
- Adapted from 2013 Les Houches wish list
  - Similar tables for other production modes incl H, W, Z, top

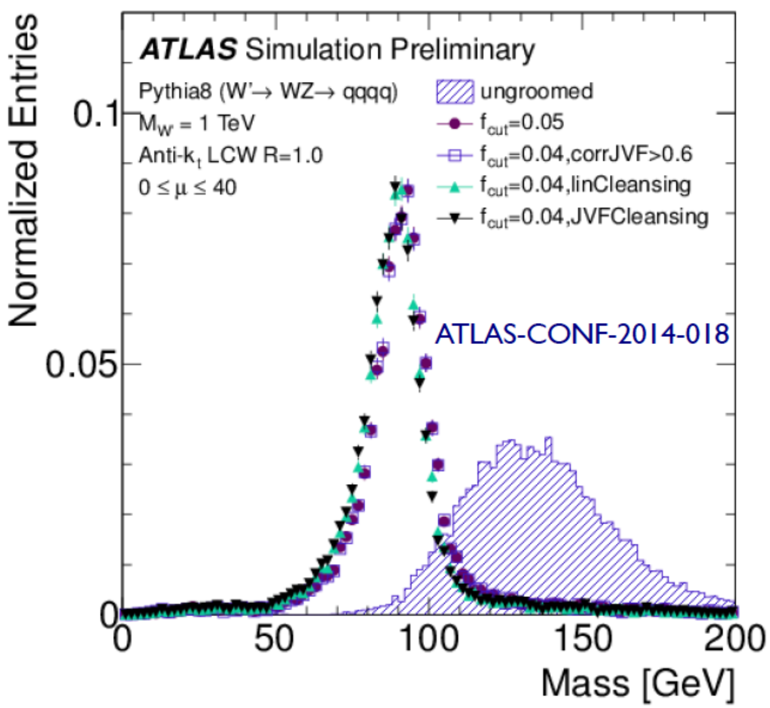
ATLAS and CMS at HL-LHC

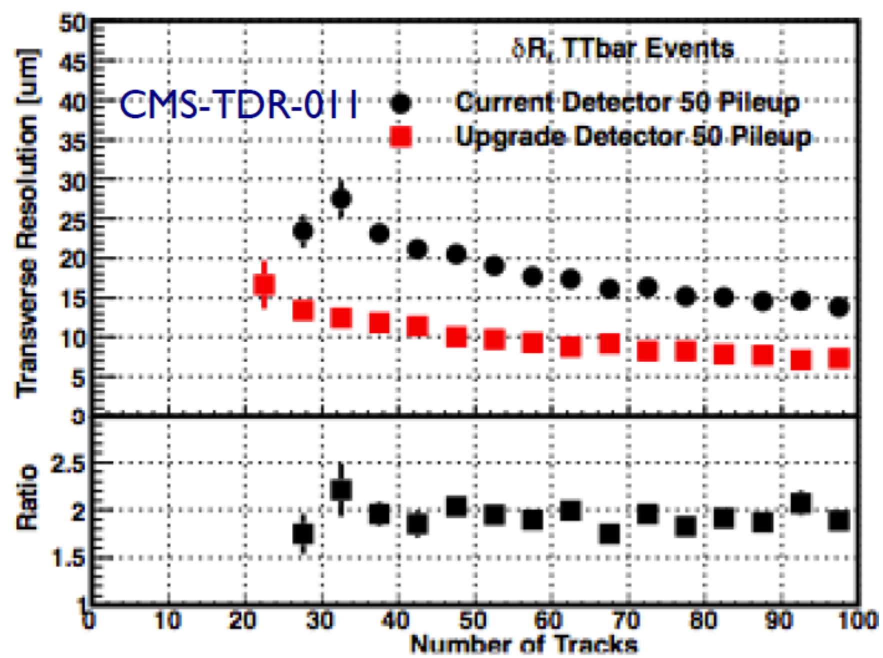
Detector challenges at HL-LHC

- 14 TeV p-p collisions
- Collect 3000 fb^{-1} total lumi
- $5*10^{34}$ $cm^{-2}sec^{-1}$ instantaneous lumi
- Pile-up of 140-200
- ATLAS and CMS upgrades:
  - New inner tracker
  - Replace electronics, upgrade DAQ
  - new/replace forward calorimeters

ttbar event with 140 pile-up events (ATLAS simulation)

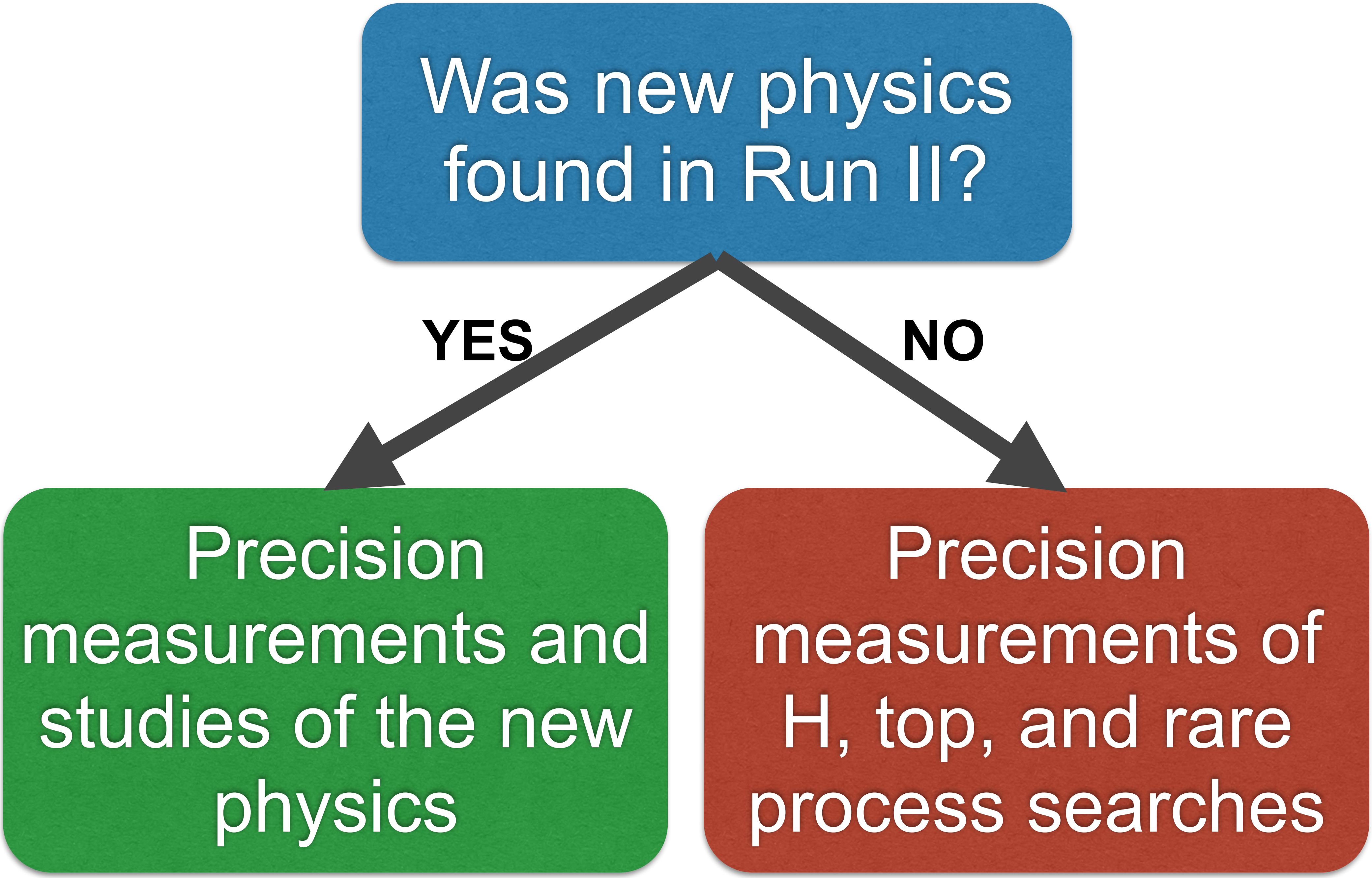




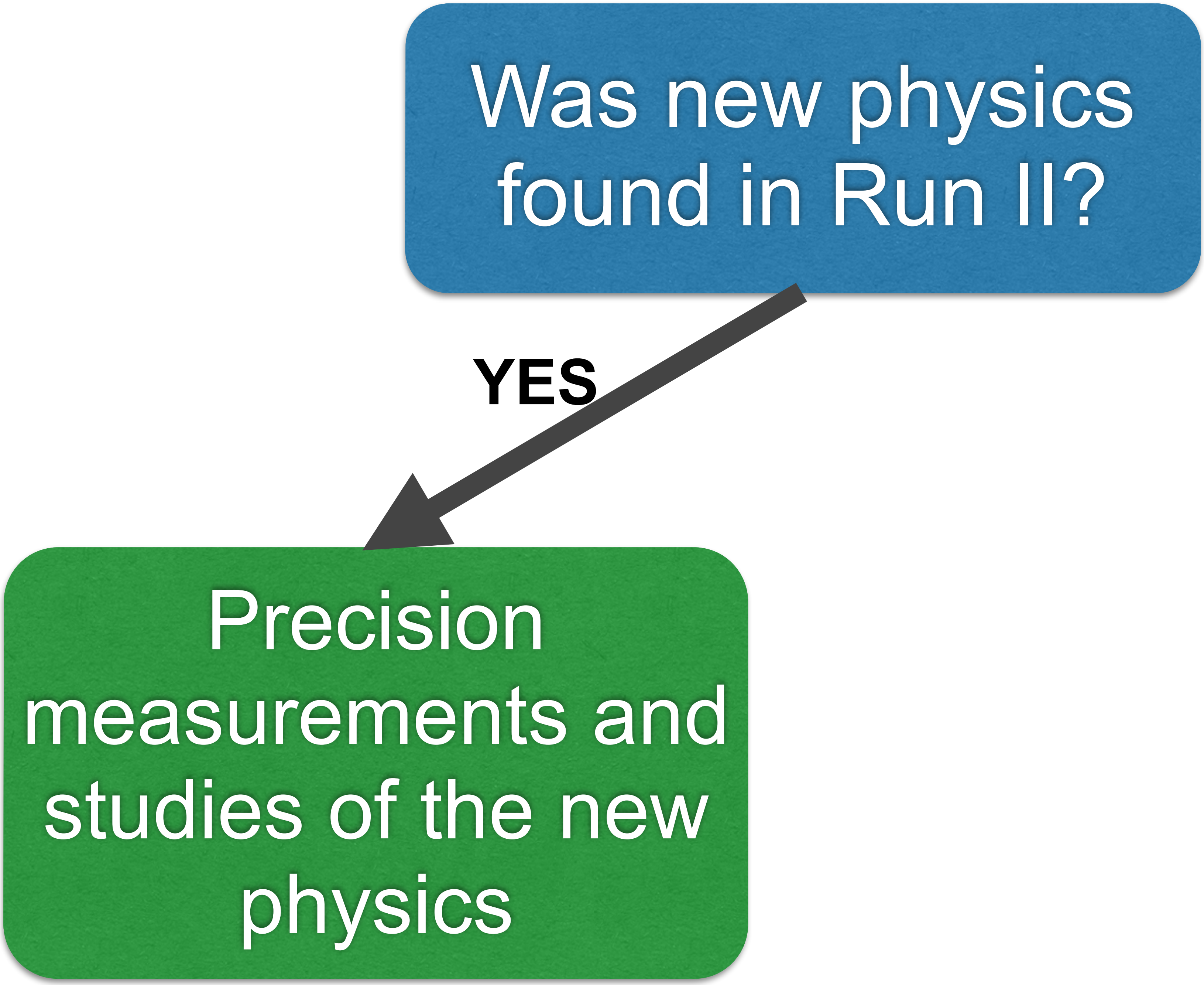


HL-LHC physics program

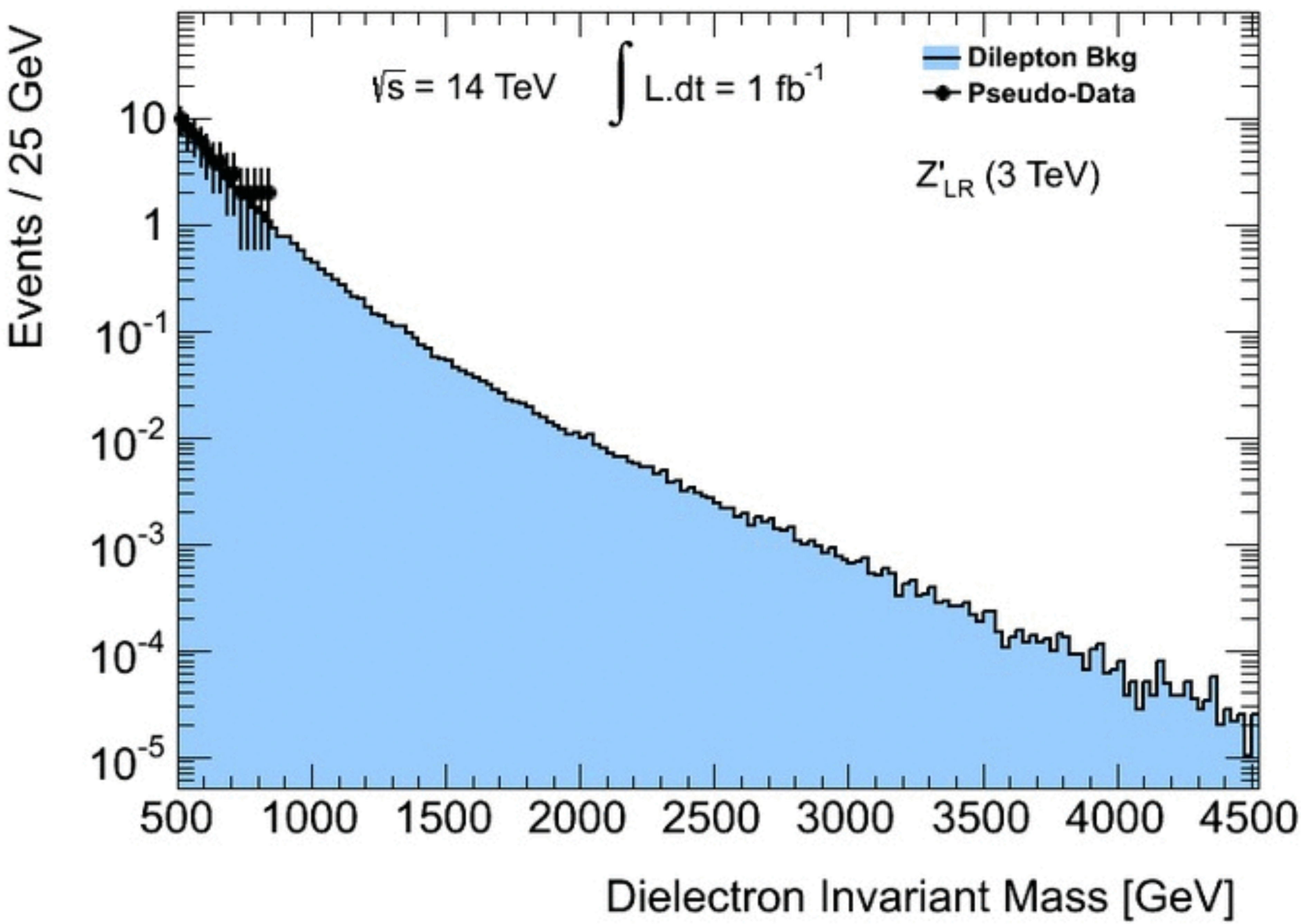
HL-LHC decision tree



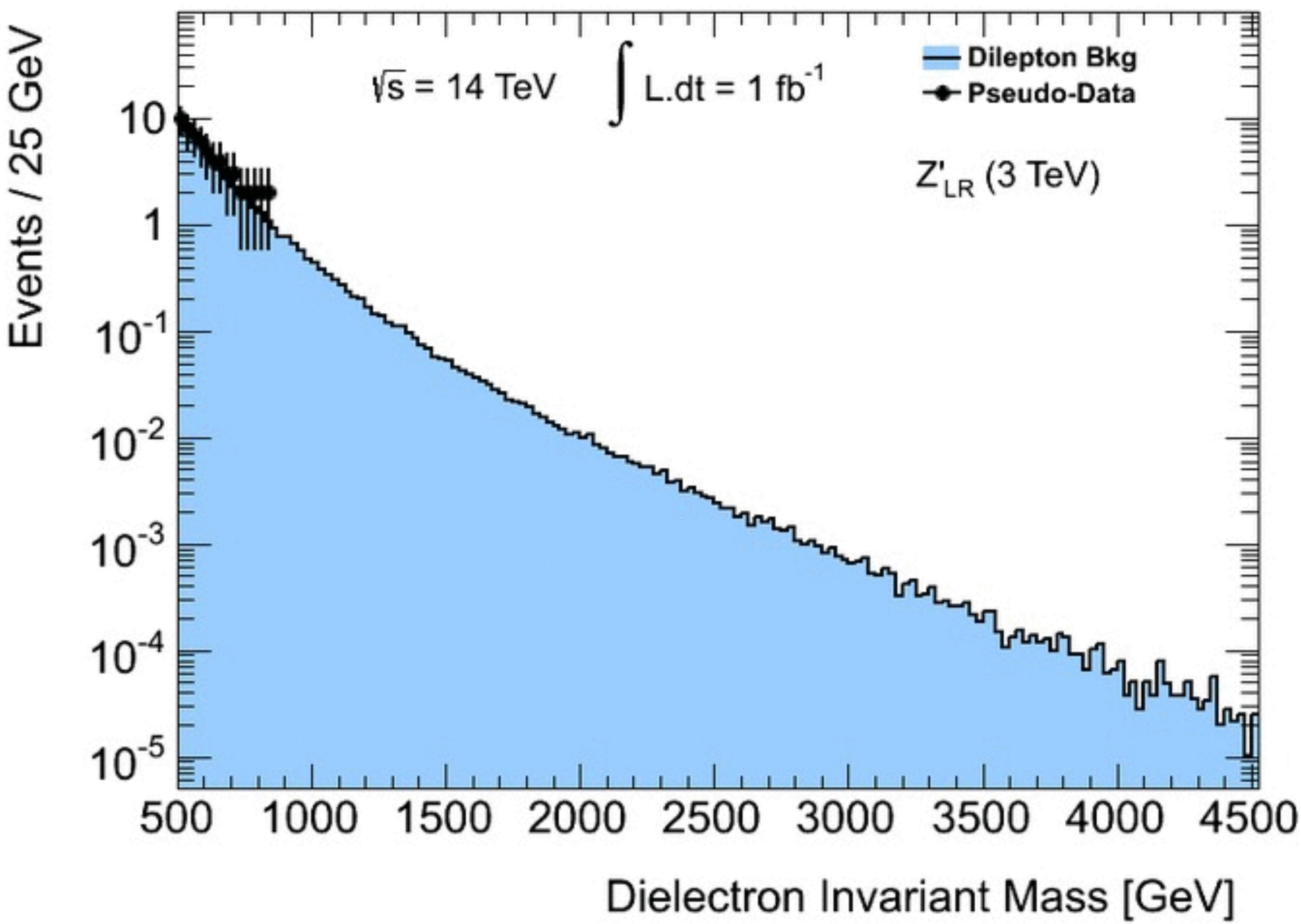
HL-LHC decision tree



High-mass resonances

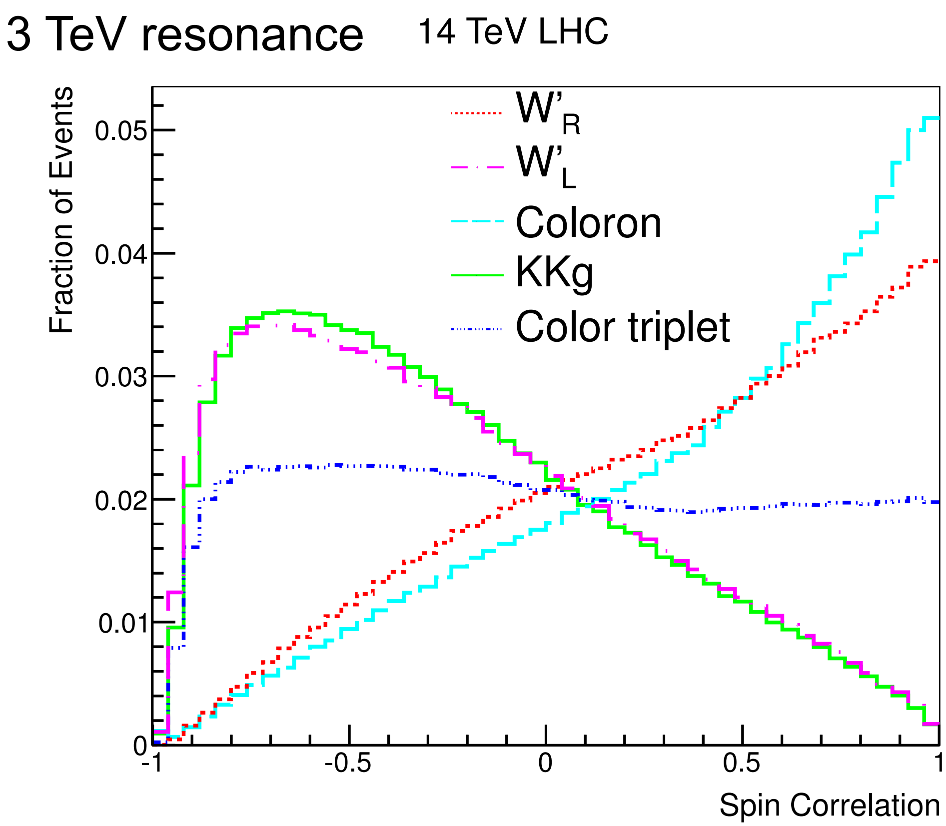


High-mass resonances

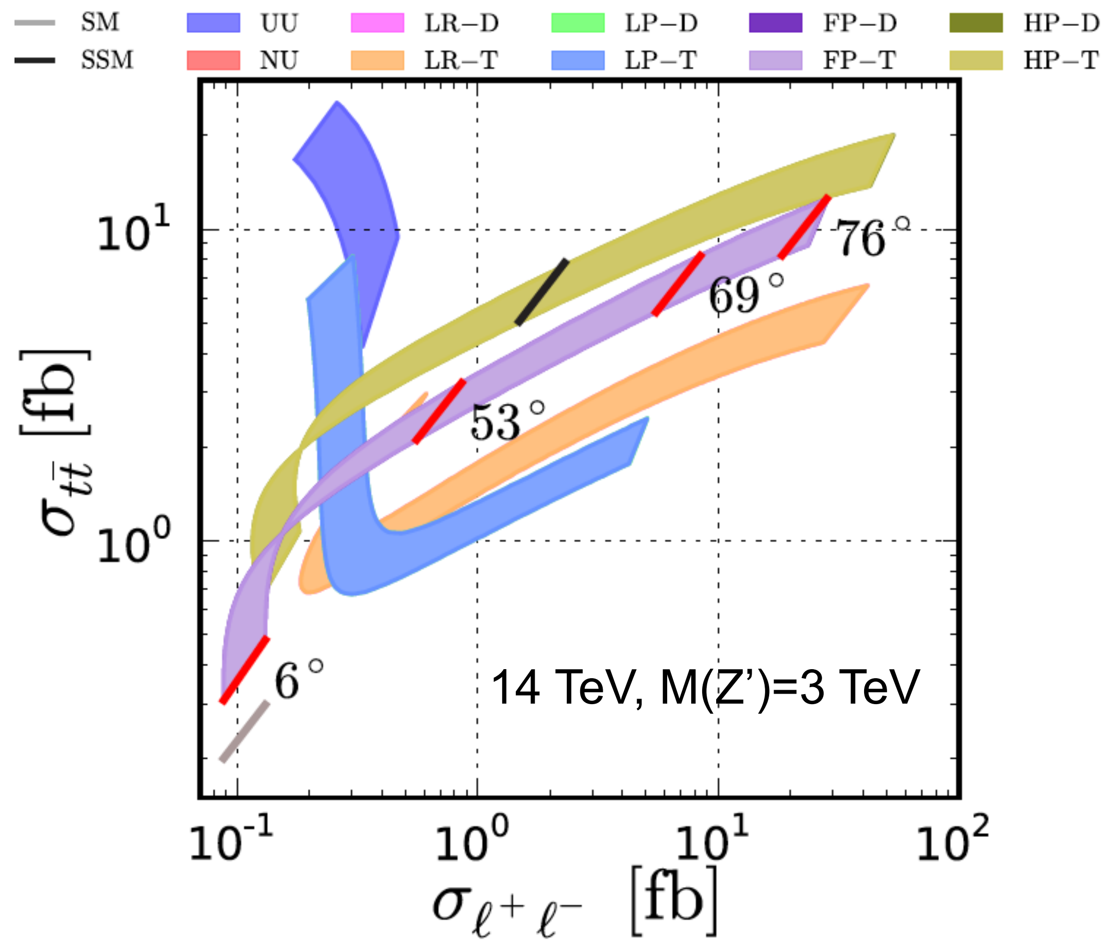


Post-observation measurements: Distinguishing new physics models

- Measurements in multiple final states
- Measurements of event kinematics



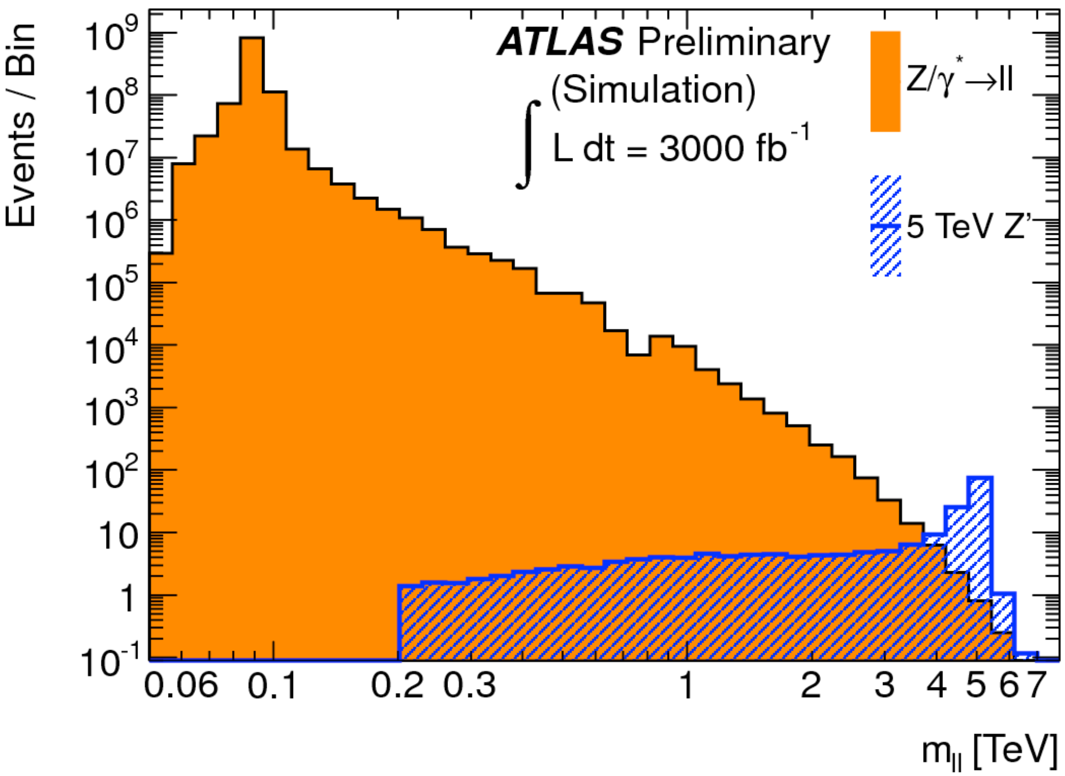
RS et al, arXiv:1409.7607



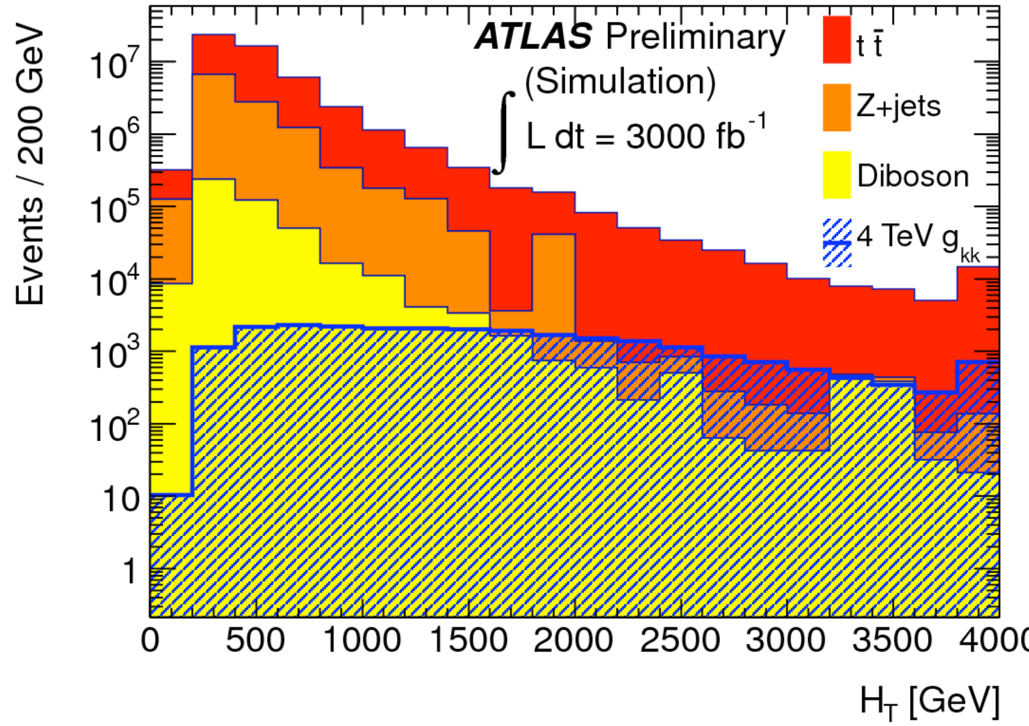
PRD86, 035005 (2012)

Resonances at HL-LHC

Dilepton



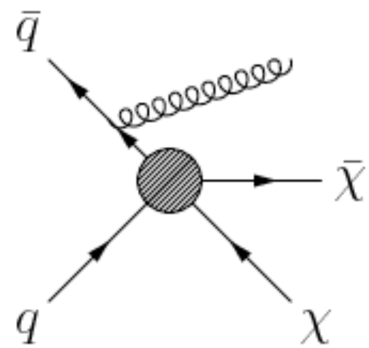
Top pair

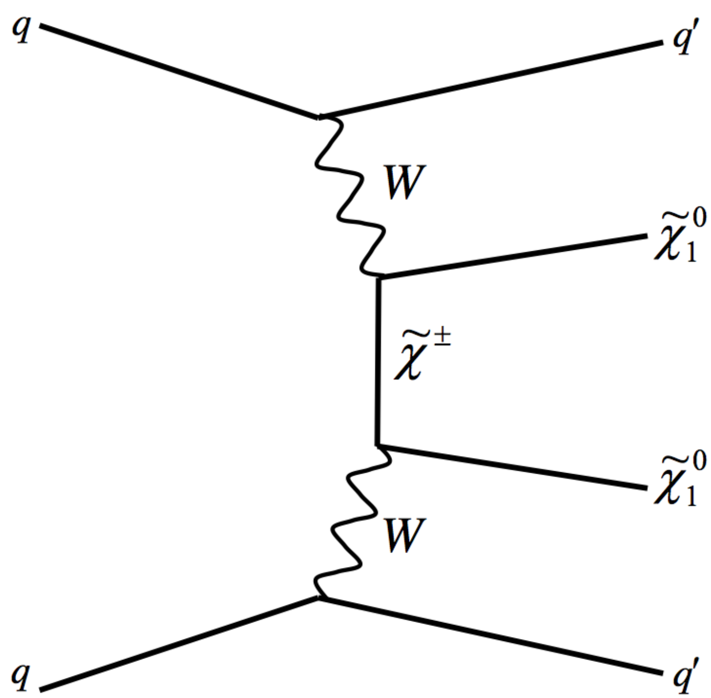


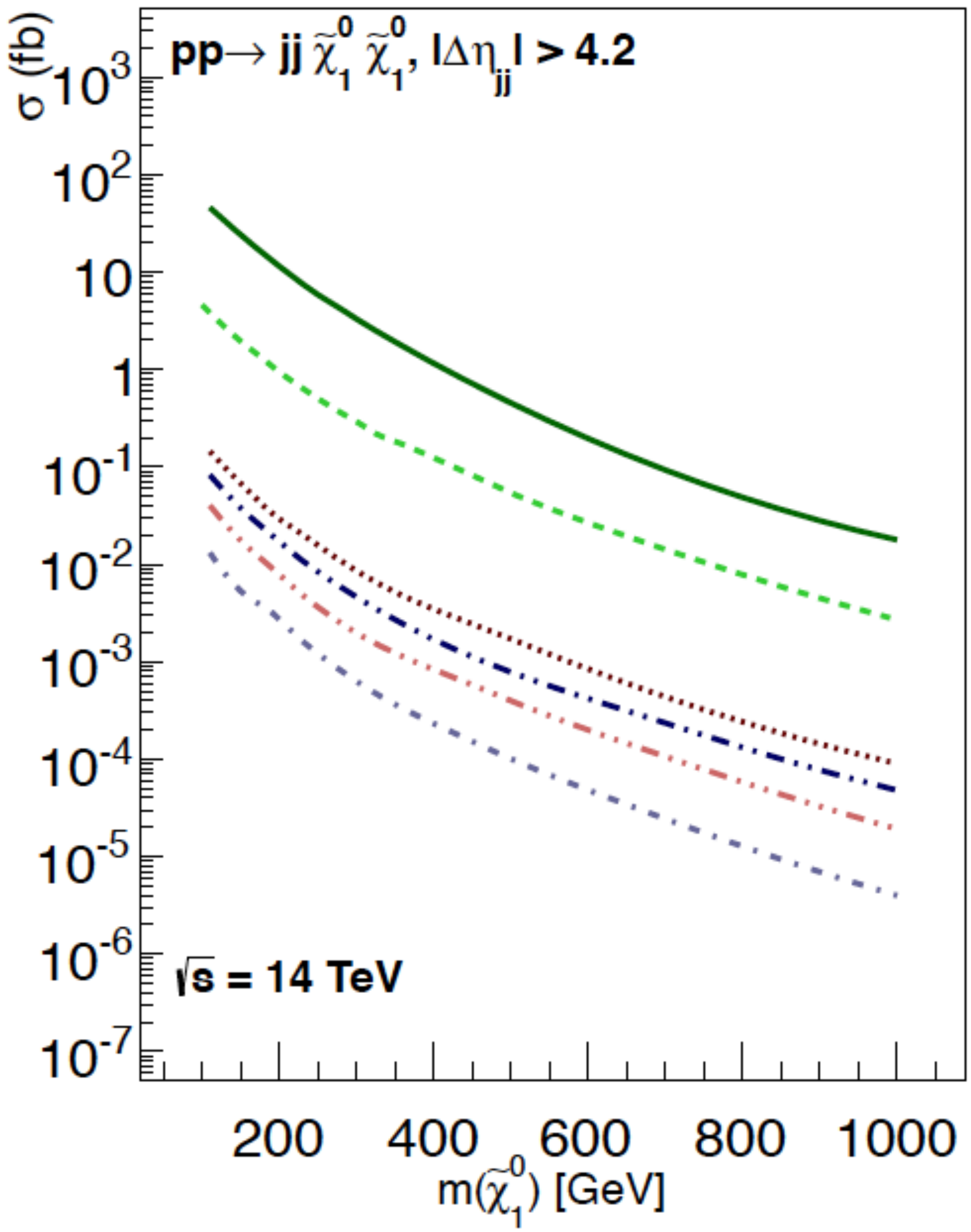
- Challenging to isolate NP signal even after observation

Dark matter

- DM production through gluon or W or Z or Higgs
  - γ + MET
  - jet + MET
  - Z + MET
  - b + MET
  - top + MET



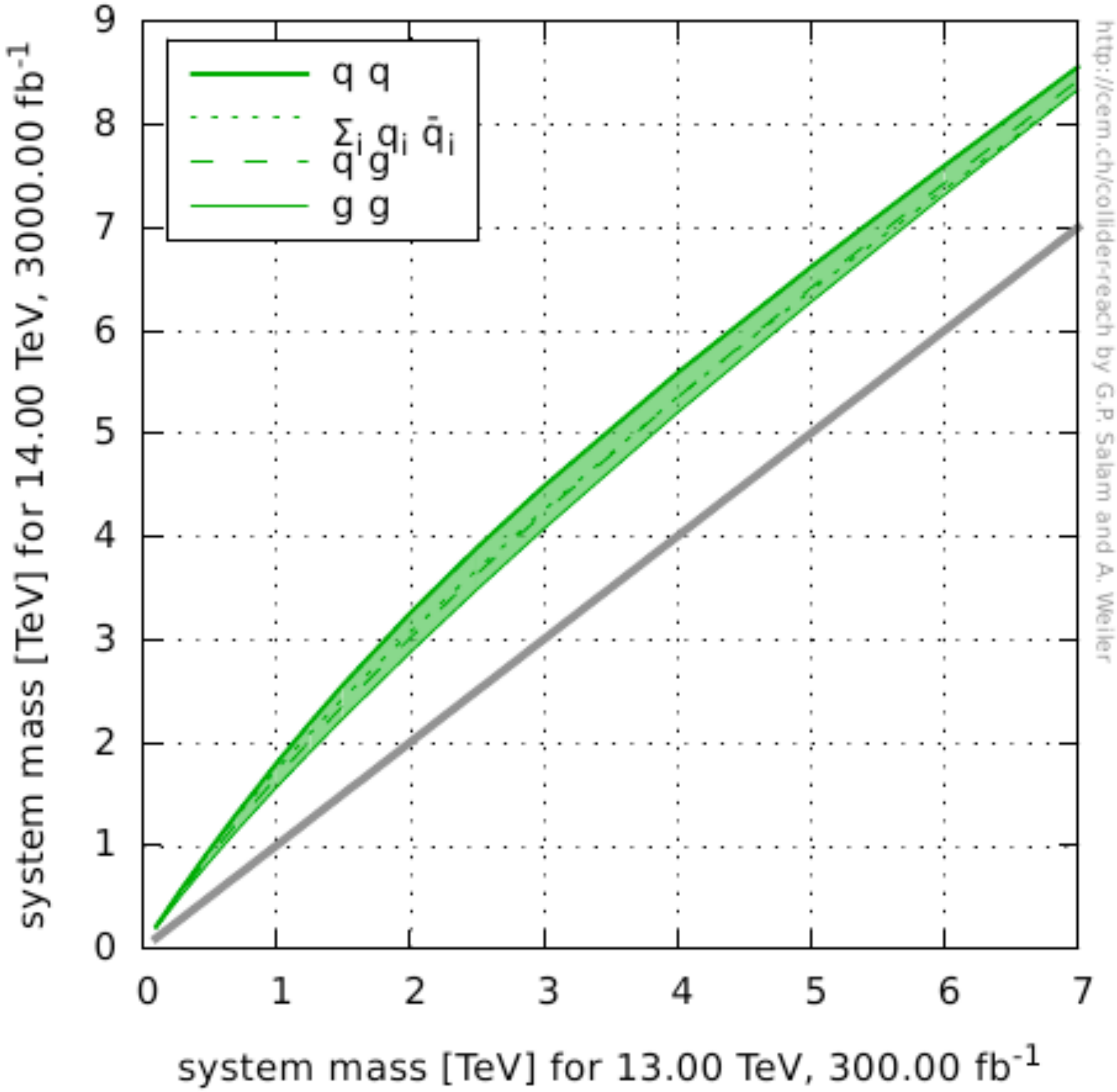




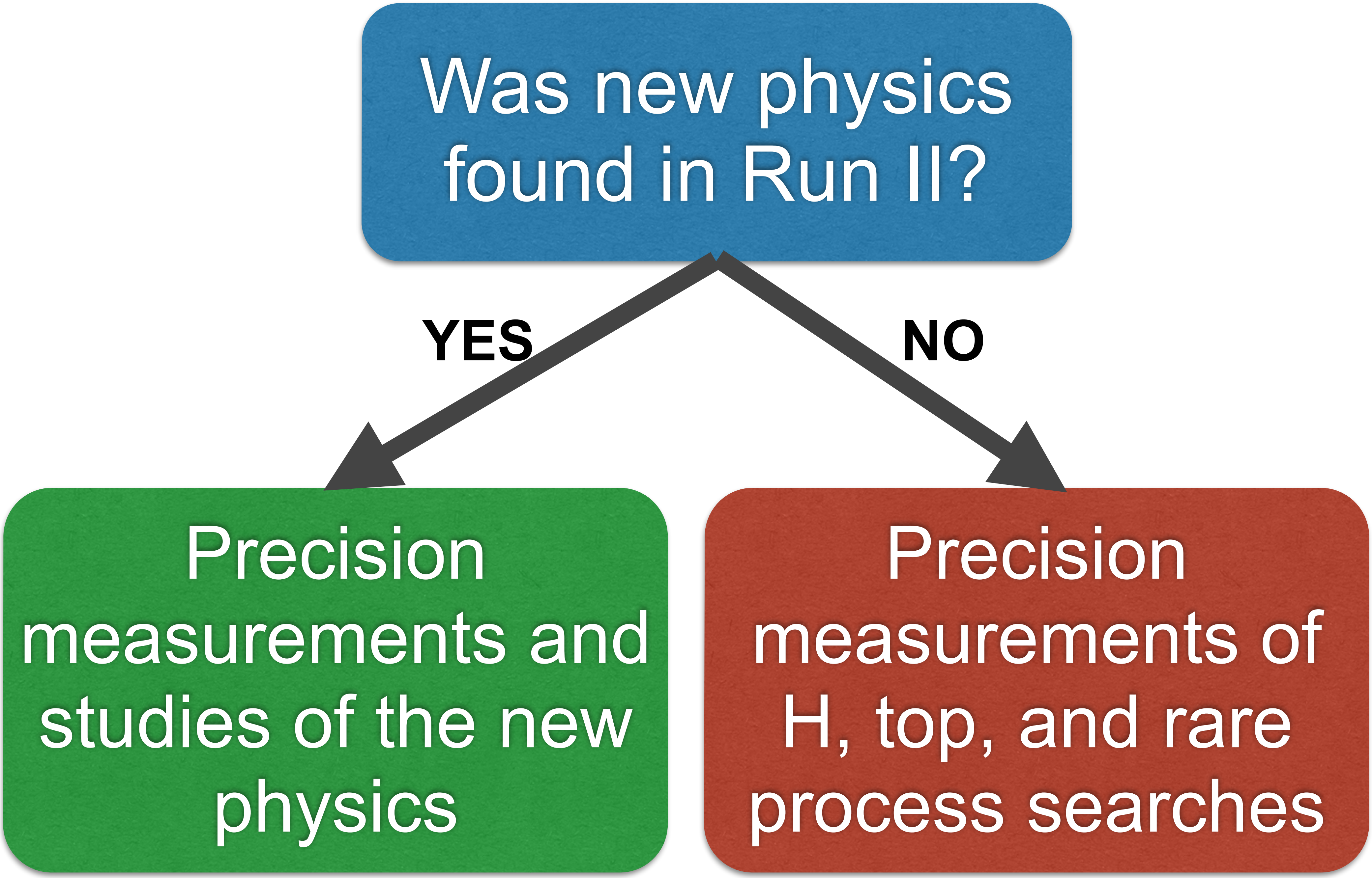
Delannoy et al, arXiv:1304.7779

High-mass resonances

- 10 × lumi = 2 × √s



HL-LHC decision tree



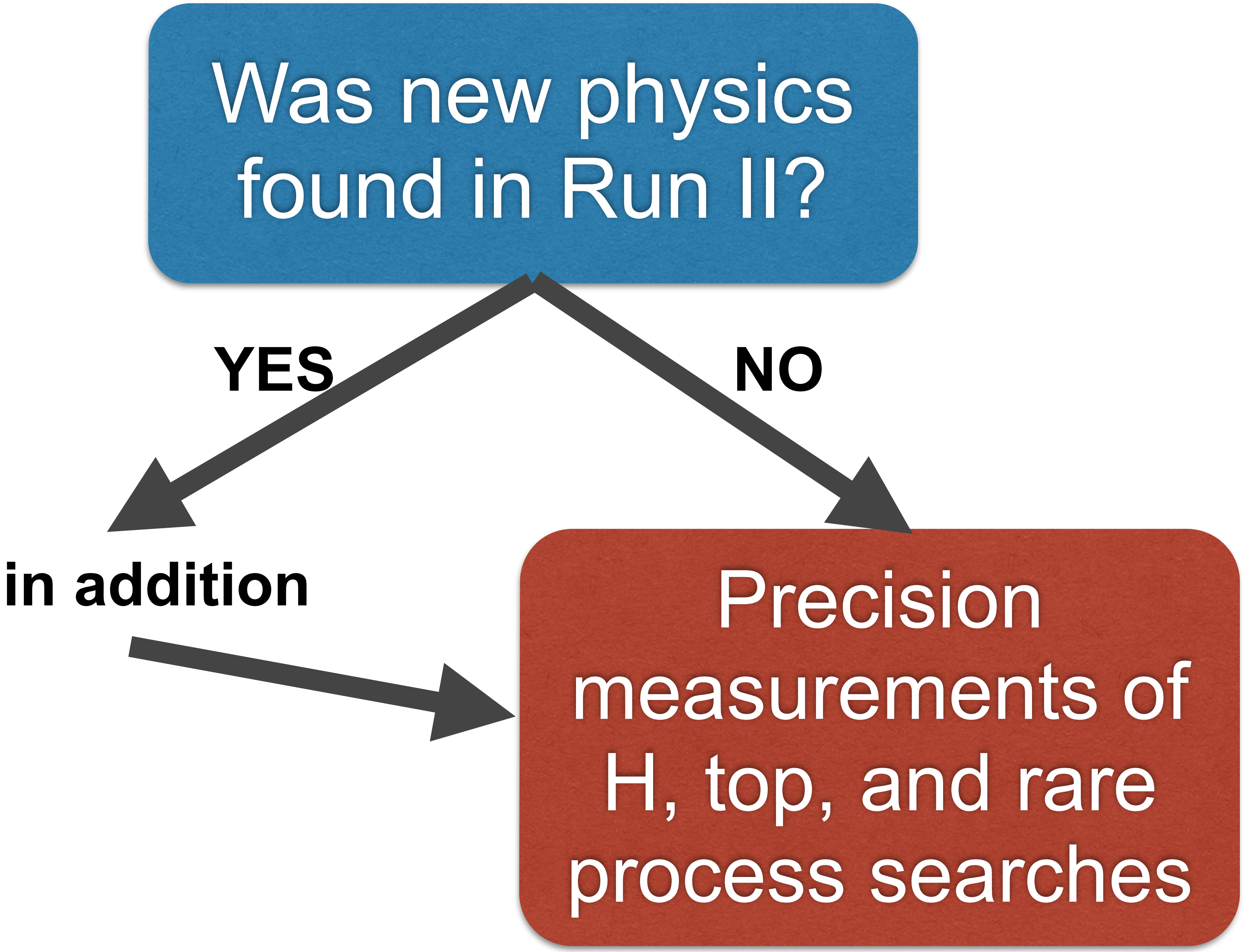
HL-LHC decision tree

Was new physics found in Run II?

NO

Precision measurements of H, top, and rare process searches

HL-LHC decision tree



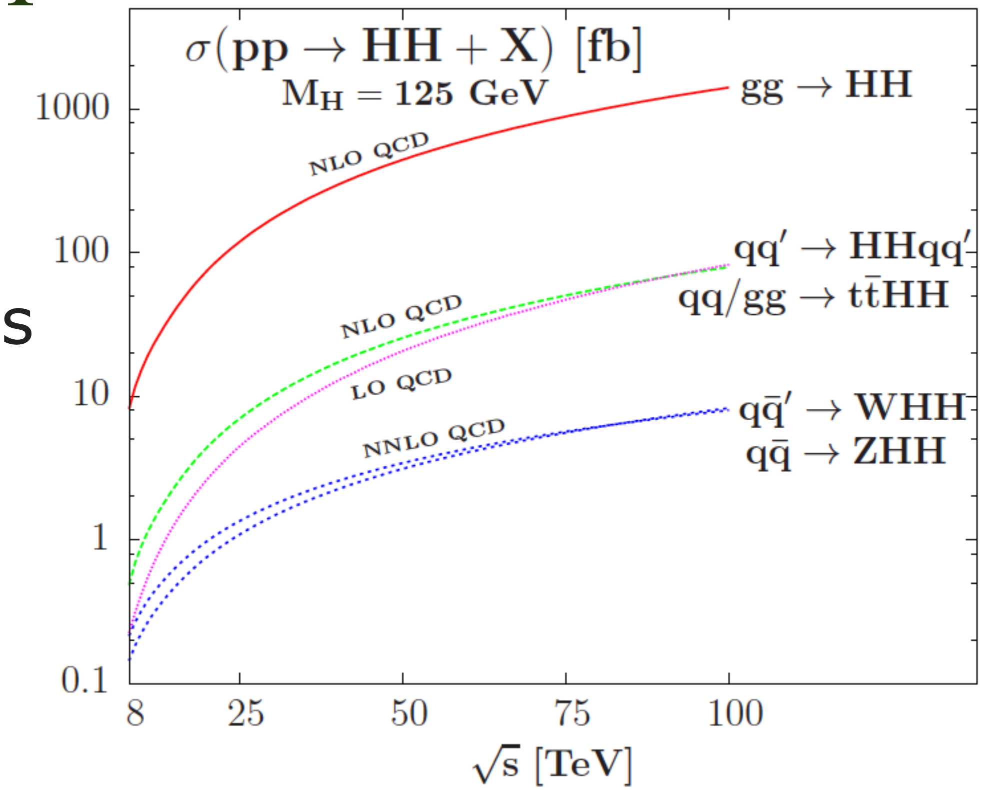
Bosons as a target and as a tool

- Study Boson couplings
  - WW, ZZ, triple-gauge couplings
  - Tri-boson, VBF WW, quartic gauge coupling

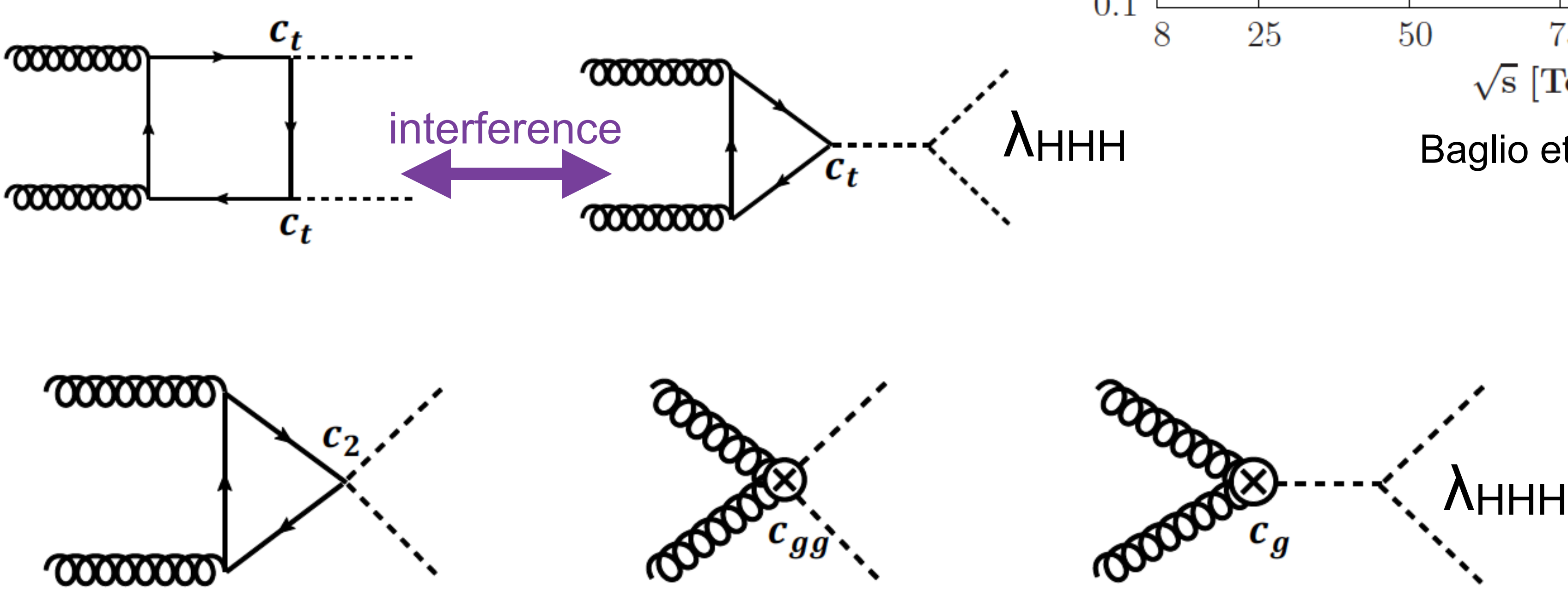
- Study Higgs production and decay
  - As many channels as possible
  - Differential cross sections
  - Rare Higgs production modes
    - HH
  - Rare Higgs decays
    - $H \rightarrow \mu\tau$
  - top → Hc
  - New particles decaying to Higgs

Double Higgs production

- Probe triple-Higgs self-couplings
  - λ_{HHH} through interference
  - In bbγγ, bbττ, bbWW
- Probe EW doublet nature of Higgs

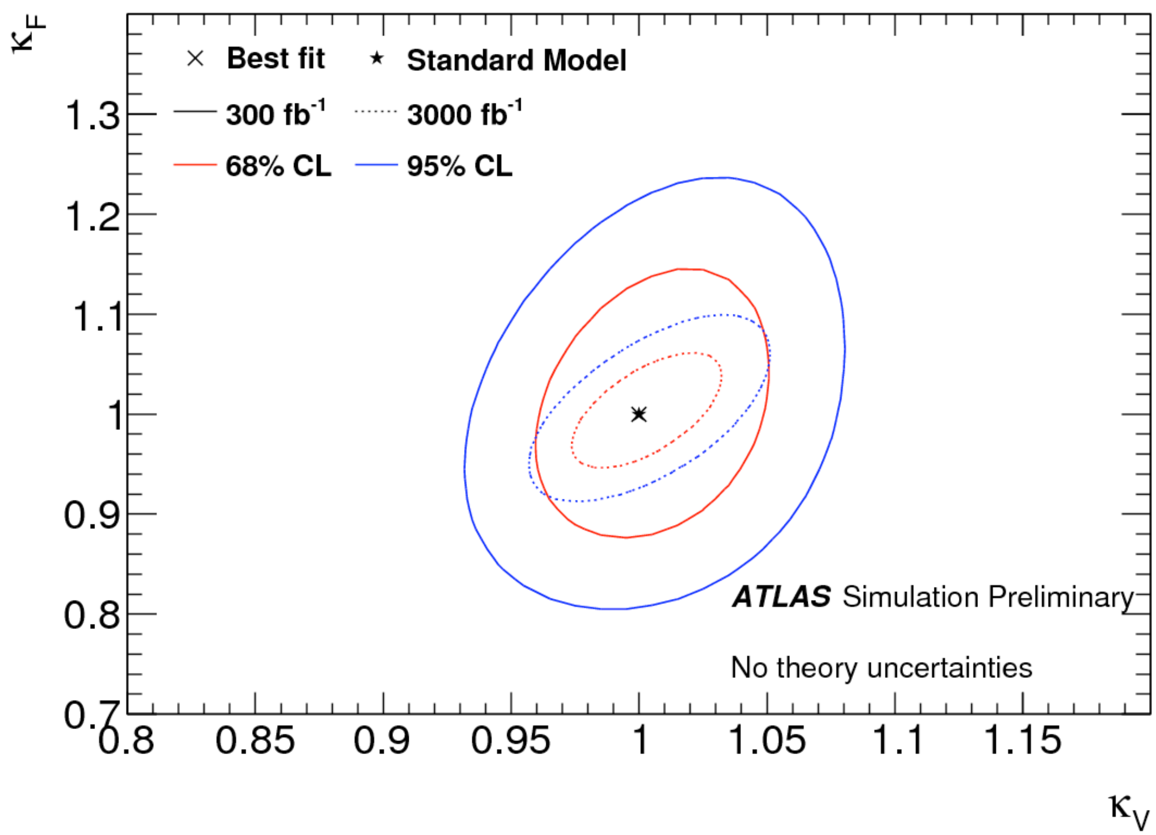


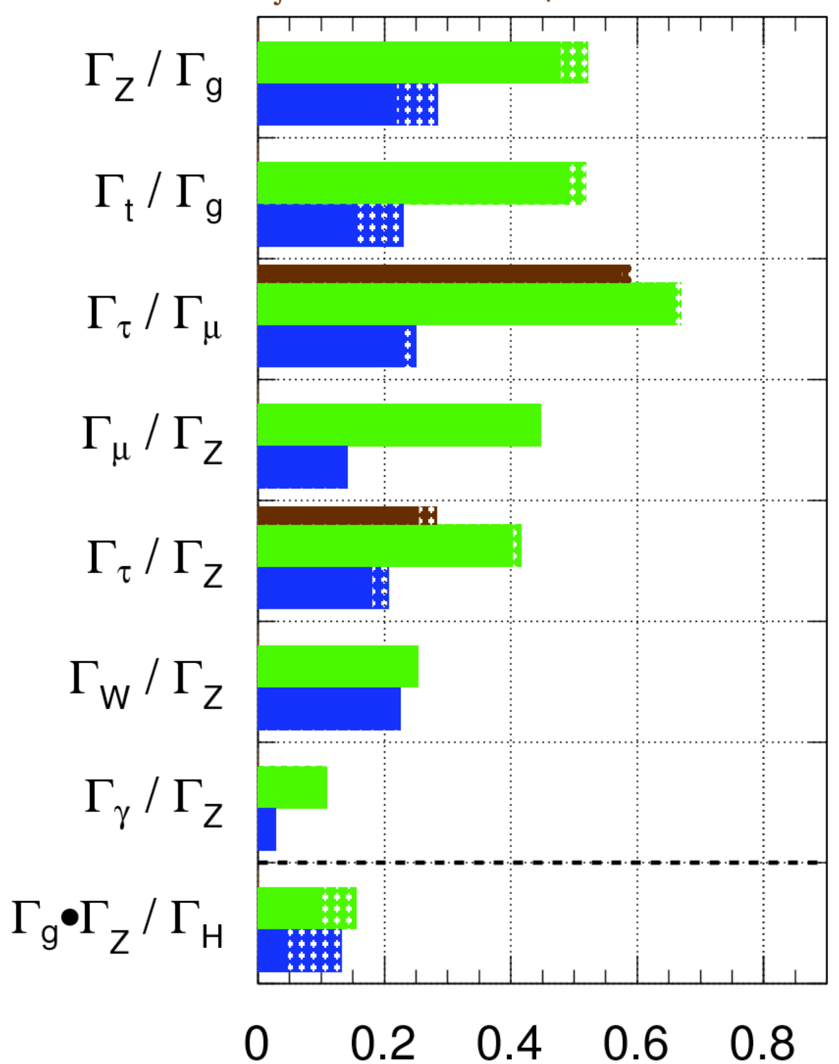
Baglio et al, arXiv:1212.5581



Higgs coupling measurements

- Observe rare Higgs decays for first time
- Disentangle different couplings through combinations





$$\frac{\Delta(\Gamma_X/\Gamma_Y)}{\Gamma_X/\Gamma_Y} \sim 2\frac{\Delta(\kappa_X/\kappa_Y)}{\kappa_X/\kappa_Y}$$

ATL-PHYS-PUB-2013-007

Top coupling measurements

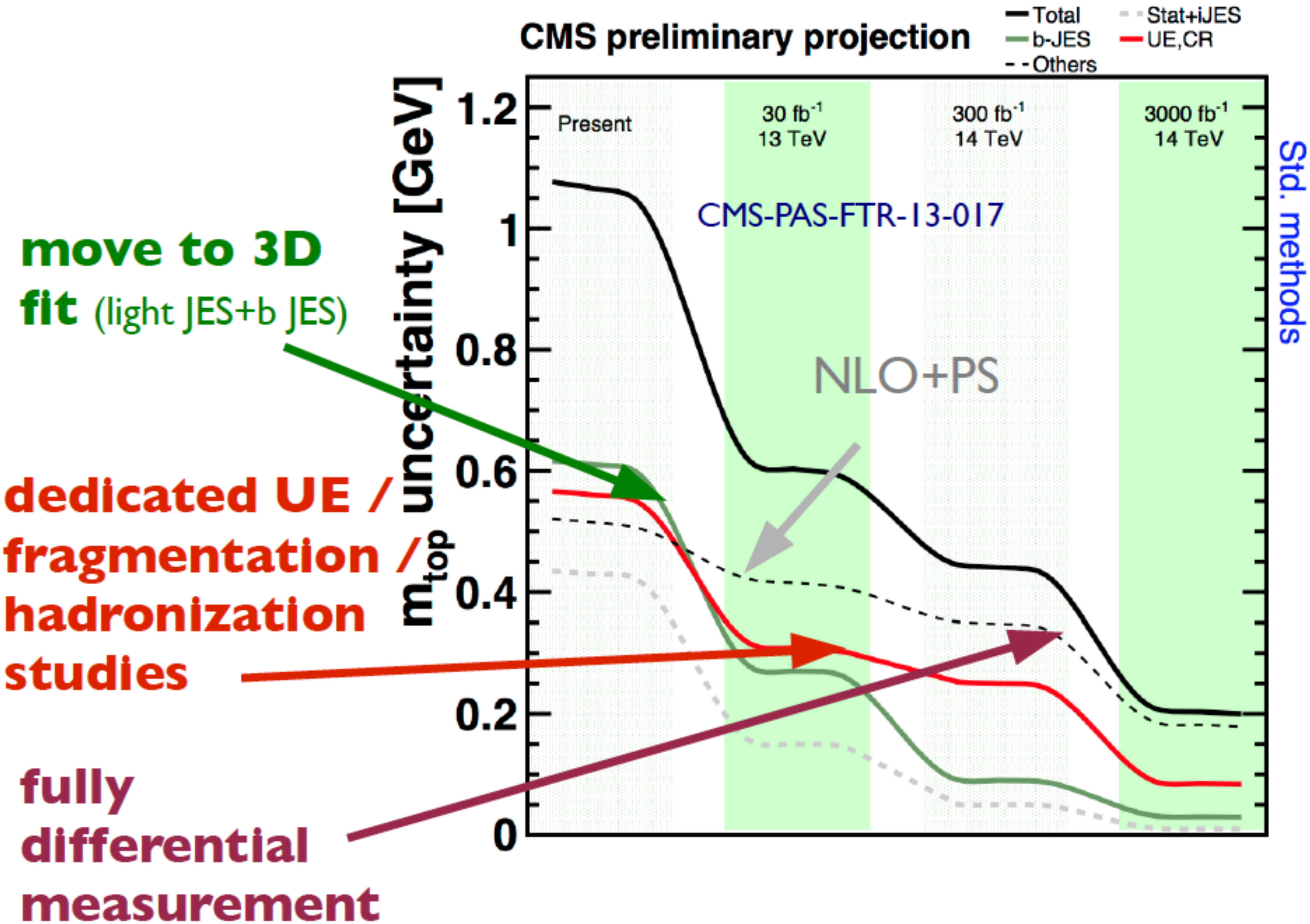
- Precision coupling measurements to W, H, Z
  - anomalous tWb couplings sensitivity 10^{-3}

Collider	LHC		ILC/CLIC
CM Energy [TeV]	14	14	0.5
Luminosity [fb^{-1}]	300	3000	500
SM Couplings			
photon, F_{1V}^{γ} (0.666)	0.042	0.014	0.002
Z boson, F_{1V}^{Z} (0.24)	0.50	0.17	0.003
Z boson, F_{1A}^{Z} (0.6)	0.058	–	0.005
Non-SM couplings			
photon, F_{1A}^{γ}	0.05	–	–
photon, F_{2V}^{γ}	0.037	0.025	0.003
photon, F_{2A}^{γ}	0.017	0.011	0.007
Z boson, F_{2V}^{Z}	0.25	0.17	0.006
Z boson, ReF_{2A}^{Z}	0.35	0.25	0.008
Z boson, ImF_{2A}^{Z}	0.035	0.025	0.015

Snowmass 2013

Precision top mass

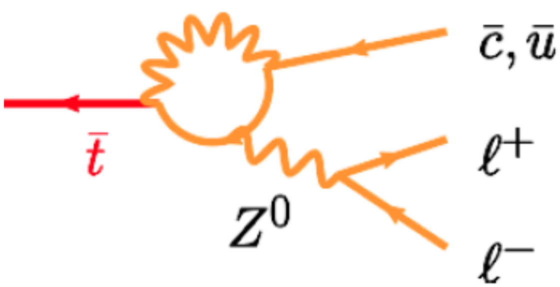
- top mass to 200 MeV
- W mass to 5 MeV

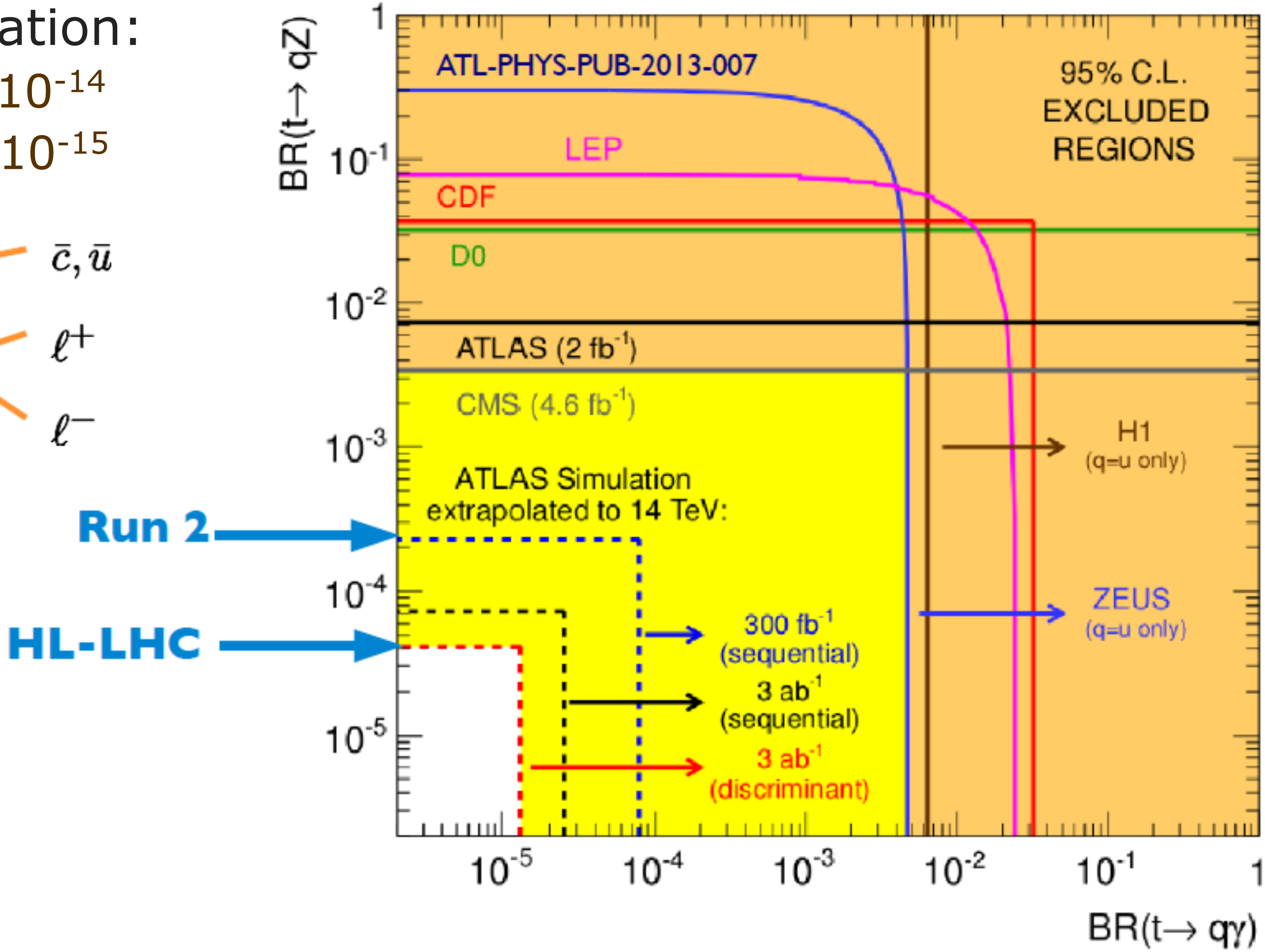


CMS-PAS-FTR-13-017

Rare top quark decays

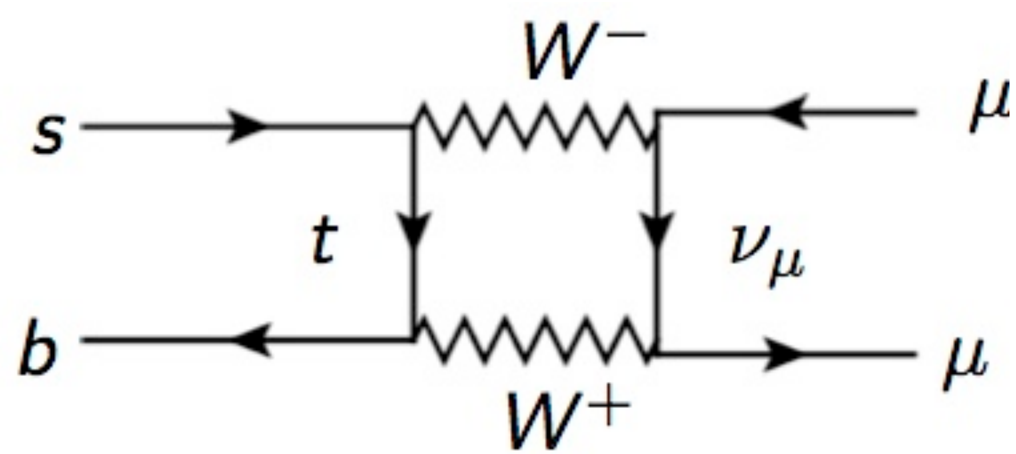
- FCNC in top, Higgs, Z
  - NP loops give ~ 10^{-5}
- SM expectation:
  - $t \to Zc \sim 10^{-14}$
  - $t \to Hc \sim 10^{-15}$

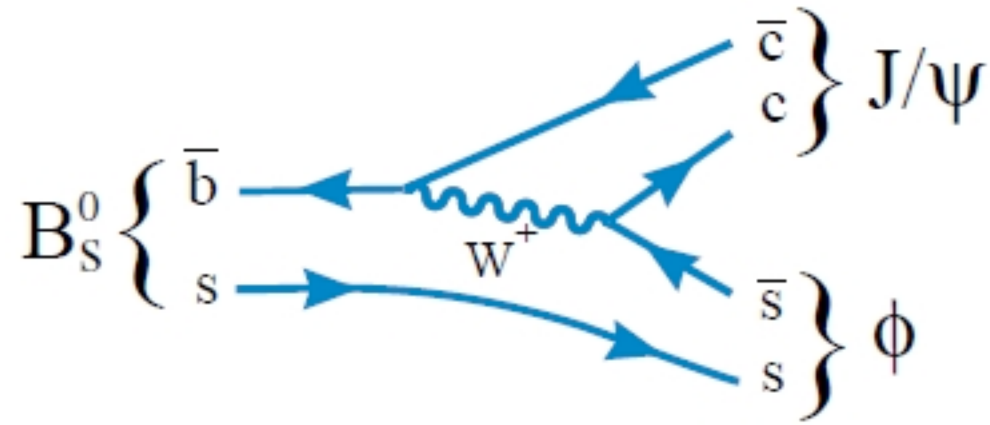




High-precision b-quark physics

- LHCb
  - Search for other sources of flavor symmetry breaking
    - Rare processes, eg $\tau \to \mu\mu\mu$, B mixing in top decays
    - $B_{s,d} \to \mu\mu$
    - CP violation in $B_s \to J/\psi\ \phi$
    - Other precision measurements and CP violation
    - Non-trivial flavor-breaking patterns





  - LHCb and ATLAS/CMS can probe indirect effects up to ~50 TeV

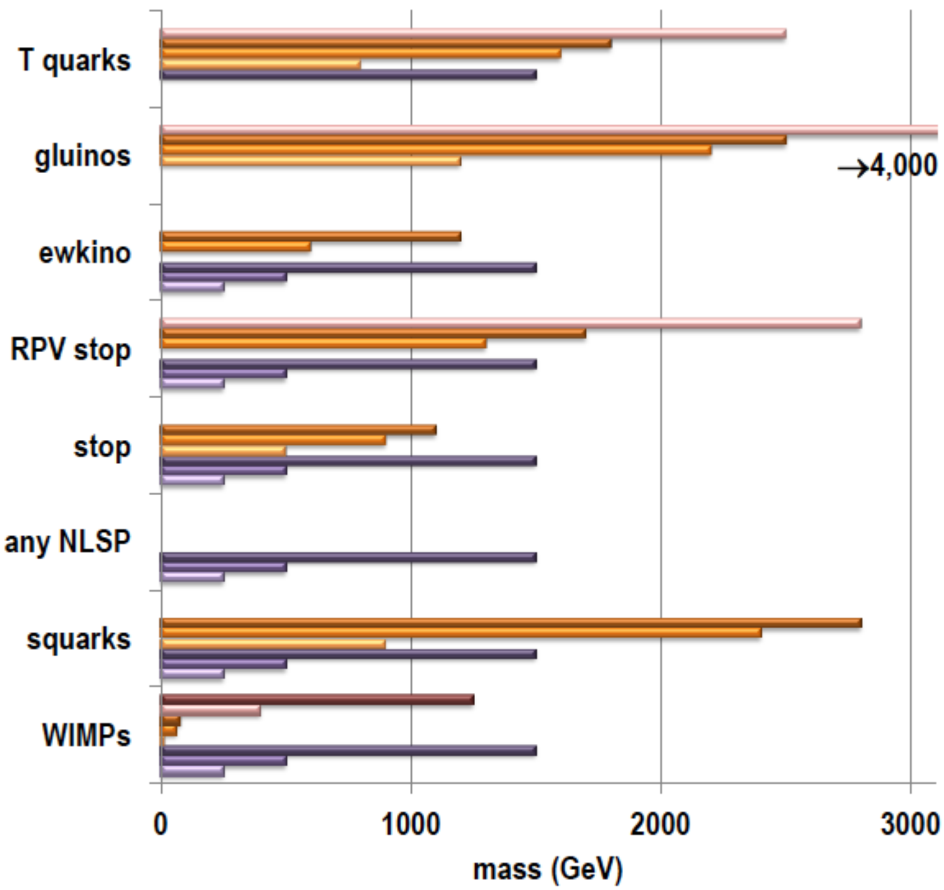
Other LHC physics

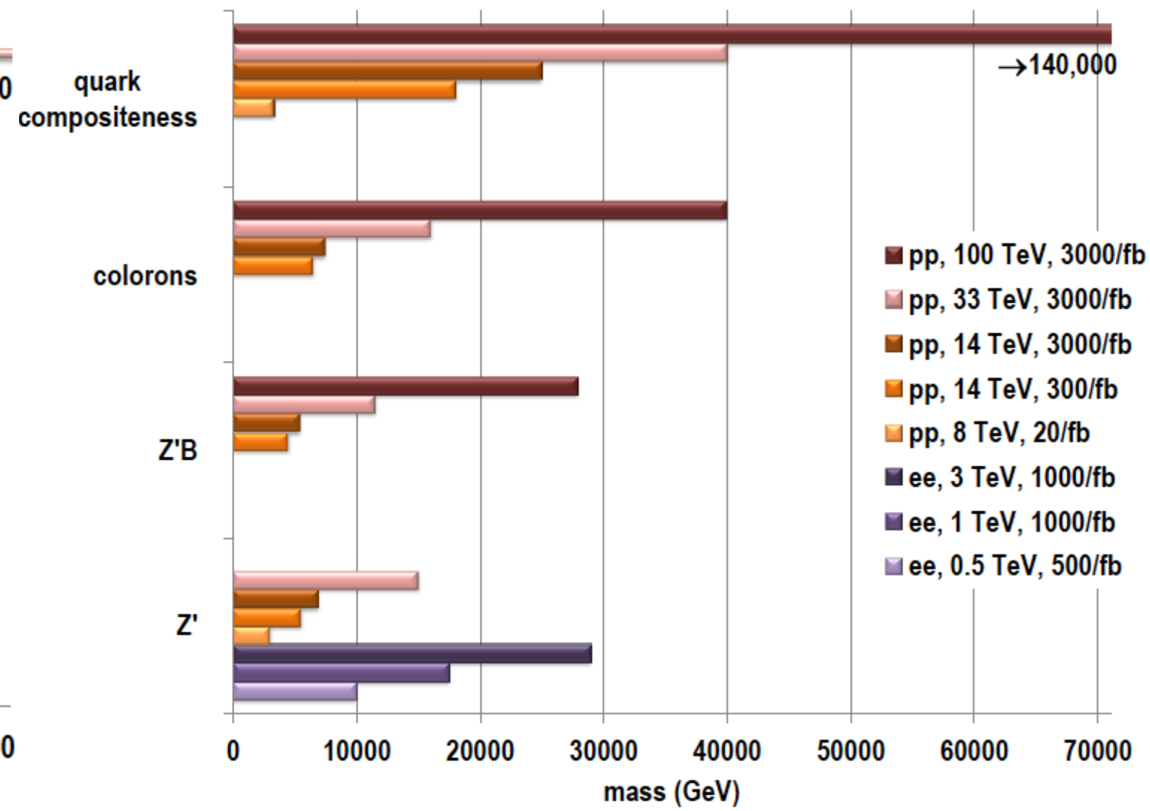
- Many other measurements by ATLAS and CMS
  - Cross sections, couplings, masses, widths, decay BRs
    - via gluon, W, Z, H
    - with top, b, W, Z, H
  - differential cross sections
    - at high $\sqrt{s}$
- Many other searches

- Heavy ion physics: ALICE
  - study rare probes in p-Pb and Pb-Pb
    - jets, b-jets, γ/Z
    - heavy flavor
  - probe confinement, transport, thermal properties of QGP

Future colliders

- 33 TeV in LHC tunnel
- VLHC - 100 TeV in 100 km tunnel
  - Complete coverage of TeV scale
- ILC - 0.5 TeV upgradable to 1 TeV
  - Highest precision mass and coupling measurements for Higgs, top, W, Z





Conclusions

- High-luminosity LHC has rich physics program
- High-precision measurements
  - Higgs, top, W, Z
  - Masses and couplings
  - test energy scales up to tens of GeV
- Measurements of new physics found in Run II
  - In many channels
  - High-mass resonances
  - Dark matter interactions with quarks, top, Higgs, W, Z
- Searches for/Measurements of rare processes
  - b-physics
  - top decays
  - Higgs decays

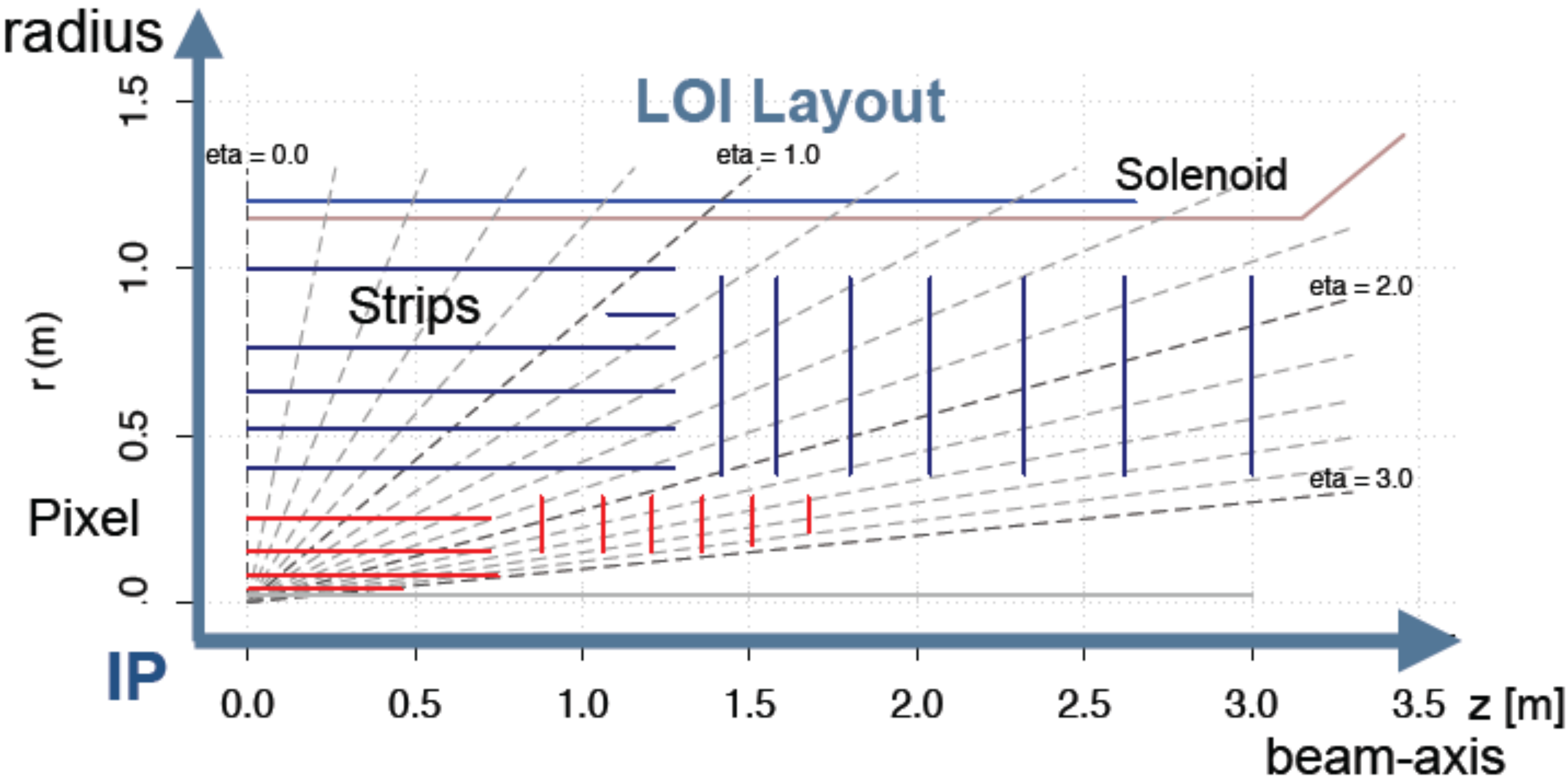
Backup

ATLAS & CMS upgrades

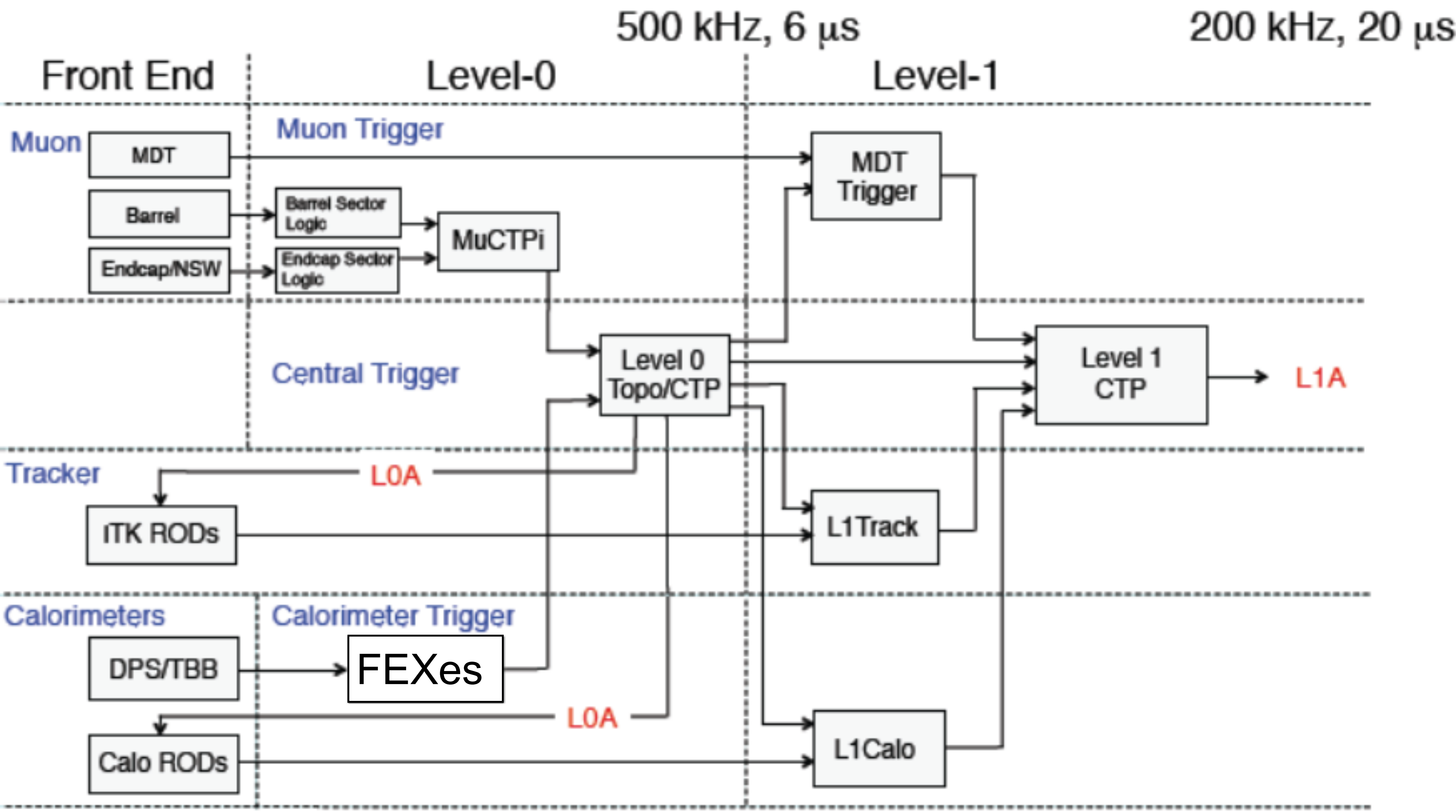
- New inner detectors
- Replace calorimeter electronics
- Replace muon electronics
- L1 track triggers
- ATLAS:
  - Level-0 trigger for calo and muon
  - Level-1 track trigger
  - Calorimeter electronics
  - Muon trigger and electronics
  - Forward calorimeters
- DAQ
- CMS:
  - Replace forward calorimeters
  - L1 triggers with more latency and higher rates

ATLAS tracking updates

- $6*10^8$ pixel channels, $7*10^7$ strip channels
- granularity increases by factor >4

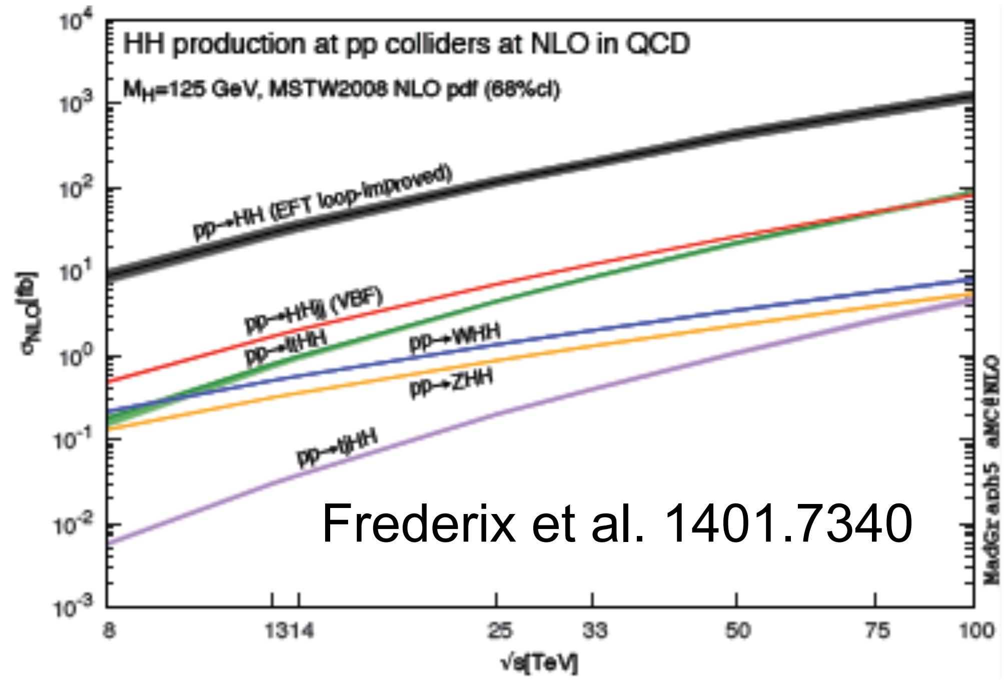


ATLAS trigger at HL

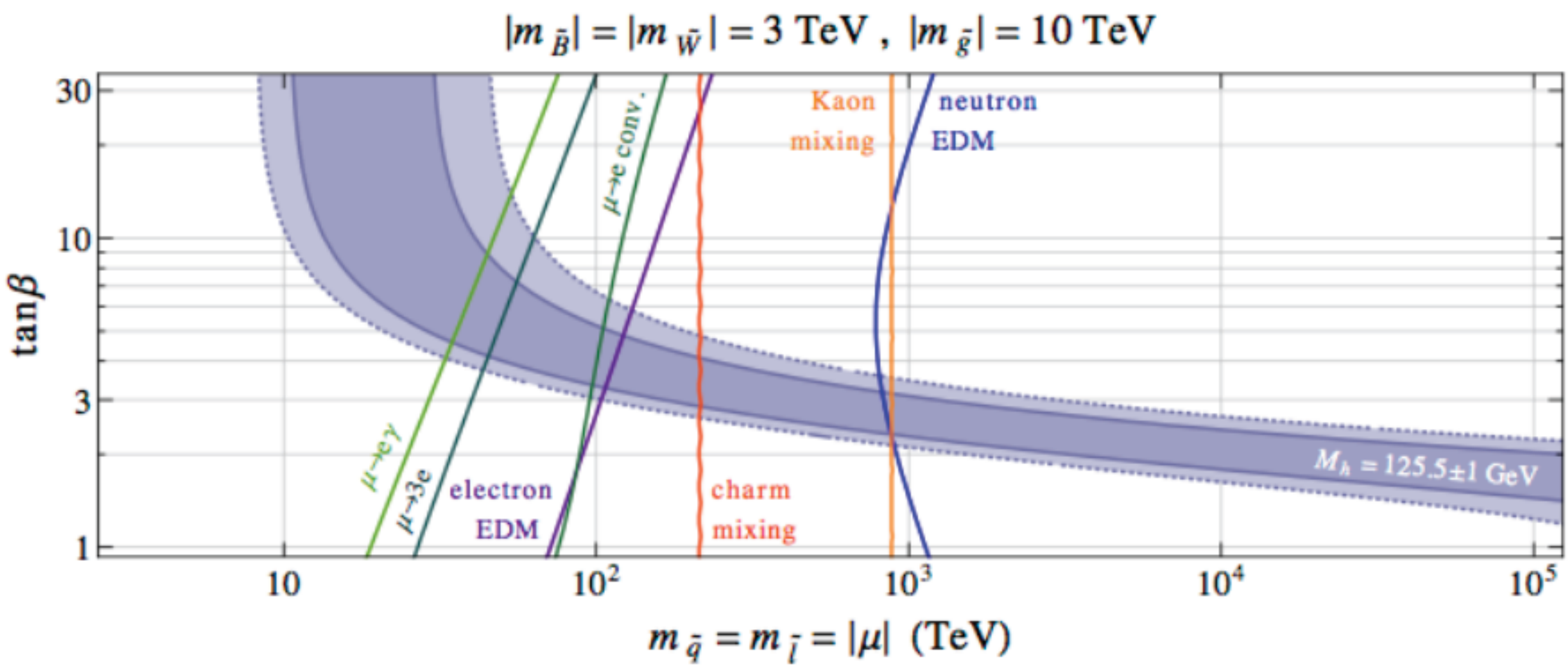


More searches

- ttHH



Mass scales of flavor measurements

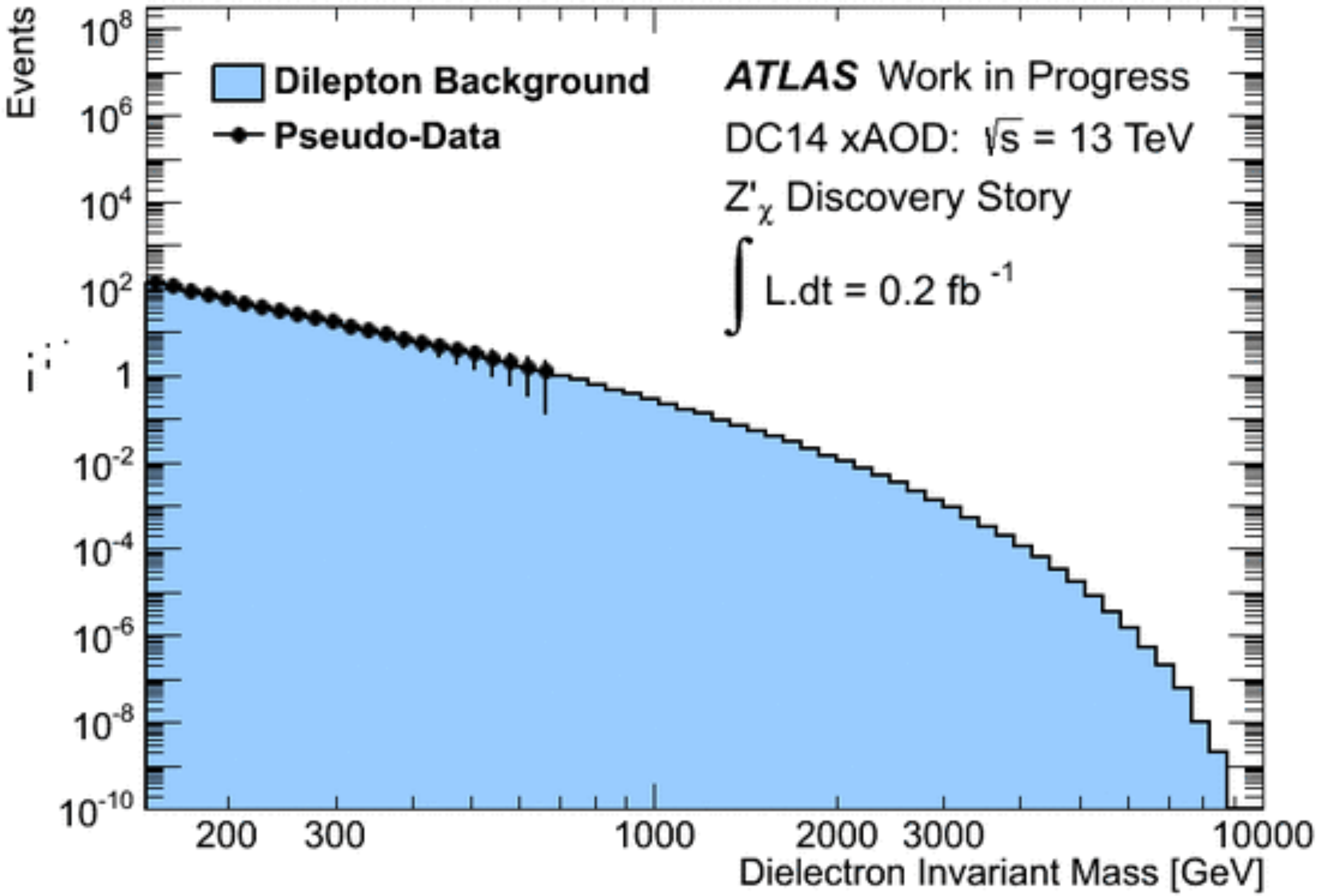


Altmannshofer, Harnik, Zupan, arXiv:1308.3653

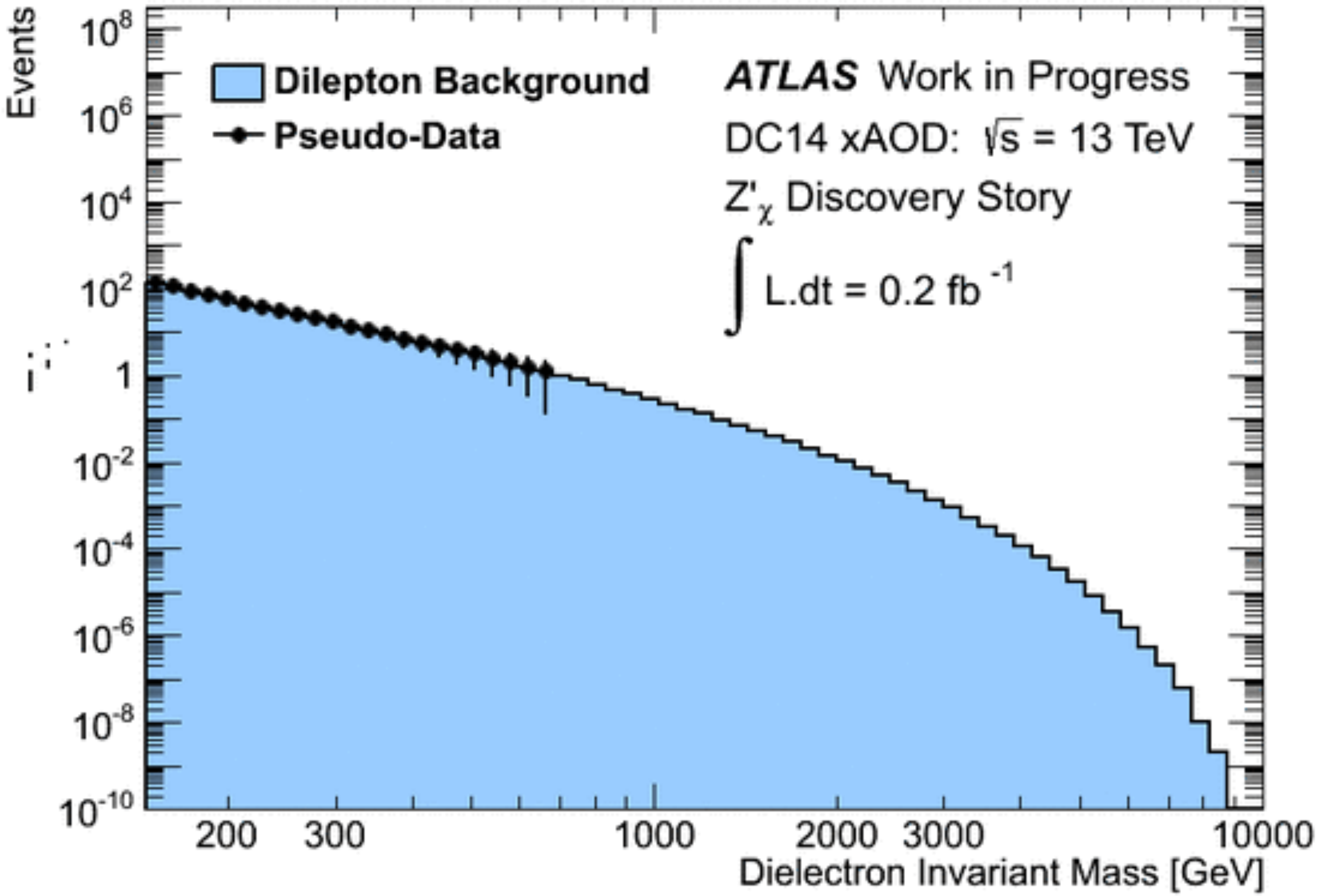
- Could also see proton decay if mass scale is 100 TeV

Hisano et al., arXiv:1304.3651

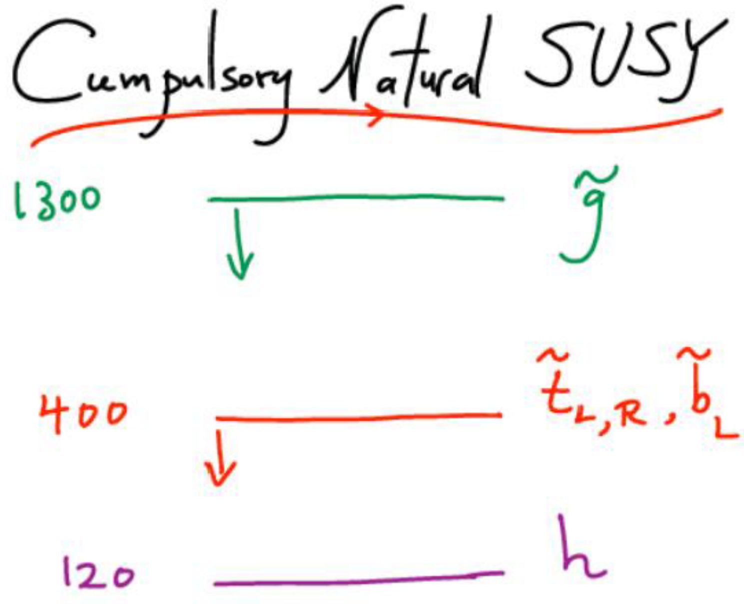
Resonance in Run 2



Resonance in Run 2



Naturalness



N. Arkani-Hamed

- Didn't see SUSY or any top partners in Run I
  - Top partners should appear immediately in Run II
  - Or could be at any mass scale (up to ~10 TeV)
- Flavor violation could have coupling O(1) if mass ~100 TeV

Physics in 2025

- Neutrino measurements

- dark matter
- fusion, ITER
- b physics
- Neutrino astronomy
  - Icecube/Pingu
- LBNF starts?
- ILC construction?